Reviewer 1

Ciscato et al.: „Impact of simulated coastal ocean alkalinity enhancement on the seasonal cycle of the air-sea CO_2 flux and surface ocean pCO_2 in European waters under a low- and a high-emission scenario "

Key results

The authors use Earth system model simulations to investigate the seasonal effect of continuous ocean alkalinity enhancement along the European coastline. They apply two emission scenarios, namely a low-emission (SSP1-2.6) and a high-emission (SSP3-7.0)scenario. The study shows that OAE enhances the additional ocean CO_2 uptake mainly in winter and lowers the surface ocean pCO_2 mainly in summer. The sensitivity of the seasonal carbon cycle towards disturbances is increased in the high-emission scenario. The authors conclude that OAE is located best in regions with a shallow bathymetry and well-mixed waters.

This study is an important contribution to the current OAE research, as it applies alkalinity addition more locally and zooms into the temporal effects of alkalinity enhancement on the ocean carbon cycle. To date, many model studies on OAE still consider large-scale or even global alkalinity additions, and investigate the effects on a rather decadal than monthly time scale. Hence, the study of Ciscato et al. improves the understanding of regional ocean alkalinity enhancement on the carbon cycle seasonality and vice versa, also because of the opposing findings of previous studies on seasonal variations of OAE efficiency (e.g., Zhou et al 20251: higher efficiency in summer than in winter; Nagwekar et al. 20242: air-sea CO_2 flux follows the seasonality of delta surface alkalinity, which is in turn determined by the MLD). The findings might be of particular interest for the development of monitoring-reporting-verification (MRV) technologies (i.e., timing of largest CO_2 uptake) as well as for the investigation of ecological effects of OAE.

While I encourage the publication of this manuscript, I also suggest some restructuring of the manuscript which might improve the clarity of the results and the findings. Most importantly, **the discussion could focus more on the interpretation of the results** (why is the timing of OAE-related changes in surface pCO_2 and enhanced CO_2 uptake different? How does this relate to the MLD and how does it go together with findings from previous studies?) **as well as on conclusions and recommendations based on the findings** (i.e., what is the best timing for alkalinity addition to be most efficient, could changes in the carbonate system seasonality and its amplitude potentially harm the ecosystem, …). Furthermore, **some rephrasing and consistent terminology** could make it easier to read the paper. Below you can find my general comments as well as line-by-line comments.

General response by co-authors

We sincerely thank the reviewer for their time and effort dedicated to this revision, which was extremely helpful in reshaping the focus of our analysis, improving the clarity of the text and re-interpreting the results in the context of the wider OAE literature. Each comment highlighted by the reviewer has been addressed extensively, following the vast majority of the suggestions / changes, as we found them essential to improve the manuscript. Multiple aspects have been largely developed, including:

- **Spatial extent of the analysis and North Sea section:** thanks to the reviewer's comments, we acknowledged that the North Sea analysis was not adding much value to the interpretation of the manuscript's results, and we decided to replace it with a consistent comparison between the 'European region' and the 'coastline region', an approach that is maintained throughout the study, both in the structure and in terminology. Thanks to this new section, an understanding of the background state of the two regions under investigation helps the reader understand changes in our OAE simulations later.
- **Addition of figures relevant to the understanding of described processes:** multiple figures have been added to the text to cover aspects such as vertical distribution of excess alkalinity, seasonal OAE efficiency metrics, carbon sequestration within and outside the region of alkalinity addition. These new figures help the reader visualise the changes described in the text regarding the seasonal cycle reversal of surface alkalinity, or the carbon sequestration potential difference between regions as well as scenarios. In addition, a table was included to summarise the main quantities described in the Results section to guide the reader throughout the text.
- **Discussion of the results and of their implications for MRV:** the interpretation of the results in the context of regional carbonate dynamics has been substantially improved to identify how and why OAE changes on one variable affect the other(s). More emphasis has been placed on the connection between surface ocean pCO_2 change and changes to the air-sea CO_2 flux, stressing the outcome that the European region turns from a system of net summer outgassing to a year-round carbon sink. The role of OAE in reversing the seasonal cycle of alkalinity has been highlighted in the context of detectability and biological risks, stressing the need for tailored MRV frameworks. The relevance of the emission scenario is also explained more in depth, drawing from previous studies that showed similar results from the ones described in this manuscript.
- **Relevance of this study and its place within the wider OAE literature:** The value of this study has been highlighted in the introduction, pointing to previous studies that only touched upon OAE-driven seasonal changes, though in a different setting than our implementation. The Discussion section now includes paragraphs that compare our study to previous research, which helps understand the new insights offered in this manuscript and its role in the wider OAE literature, while highlighting that much of the results remain dependent on features like modes, rates, locations of alkalinity addition.
- **Consistent terminology and text improvement:** following the reviewer's comments, we updated the figures and the text to be consistently referring to the same terminology, such as 'the European region' and the 'coastline region', and we address seasonal changes using the same vocabulary. Furthermore, we added definitions to the Methods (and relative figures) on metrics such as 'seasonal amplitude' and 'OAE carbon sequestration potential' to help the reader understand the dynamics described in the text, without overcomplicating its meaning. Lastly, we added more numbers to the Results section, which are also illustrated in the table.

We believe that these revisions have strengthened our analysis and enhanced its scientific rigor, and we once again thank the reviewer for their insightful feedback.

LEGEND for the review:

- REVIEWER'S COMMENT
- RESPONSE BY CORRESPONDING AUTHOR
- NEW / UPDATED TEXT

General comments

Title: The title is rather long. How about replacing "seasonal cycle of the air-sea CO_2 flux and surface ocean pCO_2" by "seasonal carbon cycle" or "seasonality of the carbon cycle"?
Thank you for the suggestion. We changed the title accordingly:

Lines 1-2: 'Impacts of Simulated Coastal Ocean Alkalinity Enhancement on the Seasonal Carbon Cycle in European Waters under a Low- and a High-Emission Scenario'

Key points / Abstract: Could the second point be more tailored towards the effect on CO_2 uptake, which is key of OAE? I.e., does it matter that surface pCO_2 is lowered in summer but CO_2 uptake is much less enhanced than in winter? Would you say that OAE should rather be conducted in winter? The third point (sensitivity of the seasonal carbon cycle) is a bit unclear – is it a general statement or relevant for OAE? If the latter, in which sense and why does it matter that OAE causes a larger disturbance of the carbonate system in a high-CO_2 ocean? Finally, point c in the abstract: yes, but I'm not sure if you can conclude this from your results. Isn't it rather that alkalinity is not exported out of the region or to depth (= circulation effect) and that these high alkalinity concentrations as you can see in Fig. 4 help to sustain a large amount of additional CO_2 uptake?
Thank you for the comments. Regarding the second point in the key points, we consciously decided to leave out any recommendations on when it would be best to deploy OAE, as we think our analysis is not able to make a clear-cut recommendation, other than acknowledging that continuous addition drives different seasonal changes from pulsed addition. Rather, we thought of pointing out that the best month to deploy OAE would depend on the features of the region, as the time lag between alkalinity addition and highest CO_2 uptake may vary depending on local conditions. In our case, local conditions of shallow MLD and fast air-sea equilibration turn the system into a year-round carbon sink, which may however not be the case elsewhere.
As per the third point in our abstract, our intention was to state that high emissions enhance the OAE-driven signal that we see in SSP1-2.6, but we see how this was not well formulated.
As per point c in the abstract, we agree that our results are not able to back such a strong statement, in addition to the fact that the North Sea section has been dropped following your and another reviewer's comments (this will be further discussed later).
We rephrased the key points and abstract, following your guidelines:

Lines 15-19:

- Ocean Alkalinity Enhancement (OAE) aims to increase the ocean's potential to sequester and store atmospheric CO_2
- Due to summer retention, surface OAE reverses the seasonal cycle of alkalinity and turns the system into a year-round carbon sink

• OAE drives the strongest CO_2 uptake change in winter, while high emissions amplify this signal

Lines 27-36:

One potentially scalable method to remove CO_2 from the air is ocean alkalinity enhancement (OAE), which works to lower its sea surface partial pressure (pCO_2) and accelerate CO_2 sequestration and durable ocean storage. This study explores how OAE might affect the seasonal carbon cycle, which plays a key role in the ocean's annual CO_2 uptake. By analysing earth system model simulations of OAE implemented continuously at the European coastline under low and high emissions, it was found that: a) due to surface alkalinity retention, OAE reduces ocean pCO_2 most strongly in summer, turning the region into a year-round carbon sink; b) the highest air-sea CO_2 flux change takes place in winter; c) the ocean's carbon sink is increased more strongly in SSP3-7.0 than in SSP1-2.6 due to a lower buffering capacity.'

Short summary: I would suggest to rather use the limited space to describe the findings of your study instead of OAE in general. I would assume that interested readers have at least a general understanding of ocean alkalinity enhancement.
Thank you for the suggestion. We modified the short summary section to focus more on the results relevant to an OAE audience:

Lines 38-44: 'Ocean Alkalinity Enhancement (OAE) is an ocean carbon dioxide removal method with large-scale potential. Using an Earth System Model, we explored the effects of continuous coastal OAE application on the seasonal carbon cycle under low and high greenhouse gas emissions. We found that surface stratification retains higher alkalinity over summer, reducing the ocean pCO_2 and turning the region into a year-round carbon sink. Additionally, high emissions lower the ocean's buffering capacity and increase the air-sea CO_2 uptake in winter'.

Methods: I suggest being careful with the term "study area" – do you use it for the North Sea only (as suggested by the subsection title of 3.1) or for the European waters as displayed in Fig. 1, red box? And then you also have the coastlines / regions of alkalinity addition, which would need a consistent naming.
Thank you for highlighting this. As it will be further argued later, we agreed with later comments that the North Sea section does not fully reflect the focus of our analysis. Thus, we decided to limit our manuscript to the comparison between the European average and the coastline of addition (see updated Figure 1 in a later response), and drop the North Sea analysis. This is how we made this clear in the text:

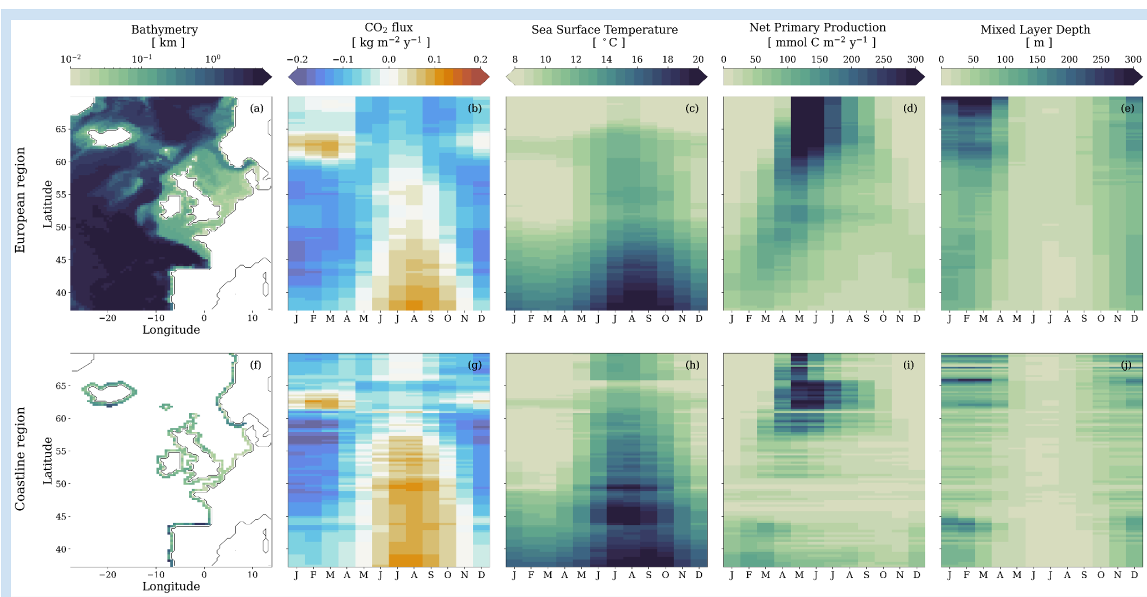
Lines 186-192: 'Our analysis focuses on the comparison between two regions: the 'coastline region', which corresponds to the shelf grid cells highlighted by the dark blue line in Figure 1b, offers details on regime shifts that take place at the epicenter of the domain; the 'European region', which corresponds to the coloured ocean region in Figure 1b, measures how the European system as a whole might respond to OAE. As Palmiéri & Yool (2024) showed that part of the OAE-driven carbon uptake can happen far from the injection region, this approach helps maintain some focus beyond the coastline of alkalinity addition without risking to dilute the OAE signal.'

Furthermore, we changed the labels of all figures to make them consistent with the namings used in the text.

Results: It is in parts unclear whether you are looking at the results of the coastal regions or of the European waters as defined in the methods; this could be added more clearly to the text. Furthermore, I do not understand entirely why you focus on the North Sea and its spatial patterns in section 3.1, while this does not play a big role in the subsequent results. I would suggest to either create similar plots as in Fig. 3 for the North Sea (and add the respective description and discussion of the results) or omit the North Sea section and focus only on the entire European waters and the coastline. For all parts, it would be useful to add a few more numbers to the text instead of only writing "is higher/lower than". This helps the reader to get a feeling for the effect range. Finally, I wonder if you could compute efficiencies (delta DIC over delta added alkalinity or delta fCO2 over delta added alkalinity) for each month, which could give you a better handle to discuss the seasonal effects of OAE.

Thank you for these suggestions. Following your comments, we applied major revisions to our manuscript and restructured part of the analysis. Acknowledging that the North Sea analysis was less necessary to address the research questions in the manuscript, we decided to replace this section with a comparison between the European region and the coastline region. We thus updated Figure 3 accordingly:

Lines 220-224: 'Figure 3: Hovmöller diagram of the zonally averaged European region (top) and coastline region (bottom) for bathymetry (a, f), the CO_2 flux (b, g), sea surface temperature (c, h), MLD-integrated net primary production (d, i), and the mixed layer depth (e, j) over the 2090-2099 mean. In the CO_2 flux plot, negative values indicate ocean uptake.'



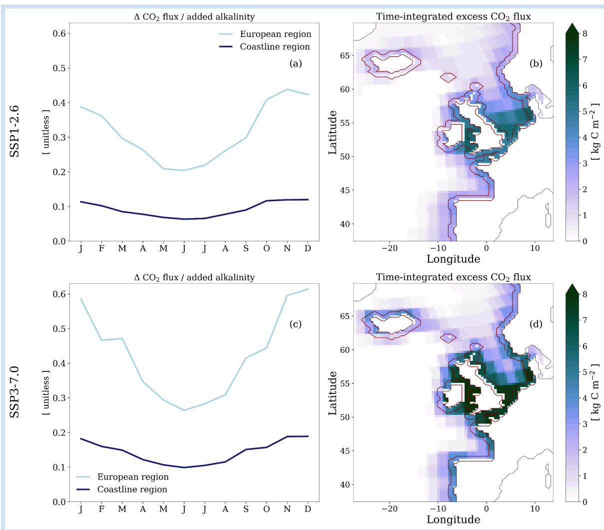
In addition to including more quantitative estimates to the text (this will be outlined later following your specific comments on this), we built a table that summarises the average seasonal values for the investigated decade. This should help guide the reader throughout the text and give more clarity to its understanding. Please, see the new table and associated caption below.

Lines 250-254: 'Table 1: Annual minimum and annual maximum values averaged over 2090-2099 for alkalinity, surface ocean pCO_2, the air-sea CO_2 flux, and the mixed layer depth. Results are presented for the European region and the coastline region under both emission scenarios in the control and OAE runs. Note that air-sea CO2 flux negative values indicate uptake by the ocean.'

	European region				Coastline region			
	SSP1-2.6		SSP3-7.0		SSP1-2.6		SSP3-7.0	
	Control	OAE	Control	OAE	Control	OAE	Control	OAE
Alkalinity [µmol kg-1]	(2198, 2210)	(2315, 2327)	(2167, 2184)	(2298, 2314)	(2184, 2203)	(2563, 2672)	(2138, 2162)	(2547, 2685)
Surface ocean pCO2 [µatm]	(404, 433)	(357, 374)	(745, 807)	(674, 719)	(391, 452)	(188, 238)	(730, 836)	(344, 461)
Air-sea CO2 flux [kg m-2 y-1]	(-0.102, 0.009)	(-0.235, -0.067)	(-0.142, 0.038)	(-0.327, -0.053)	(-0.111, 0.03)	(-0.539, -0.209)	(-0.139, 0.061)	(-0.823, -0.318)
Mixed layer depth [m]	(15, 135)	(15, 141)	(14, 107)	(14, 106)	(15, 76)	(15, 75)	(14, 68)	(14, 66)

Concerning efficiency, we consciously decided to not focus our manuscript on OAE efficiency, as we thought that this would have slightly shifted the focus of our paper. Additionally, another paper is being drafted at the moment which will more extensively focus on OAE efficiency using the same simulations. However, following your comment, we decided to add a figure that shows the seasonal 'carbon sequestration potential' of OAE for the different regions and scenario, arguing that higher potential in the European region compared to the coastline is due to the fact that excess CO2 uptake is not limited to the region of alkalinity addition, challenging MRV metrics and country- / regional-level accountability. Please, see the figure and associated text below:

Lines 384-388: 'Figure 7: The seasonal carbon sequestration potential defined as the ratio between the change in CO_2 flux and the added alkalinity carbon equivalent averaged over 2090-2099 (a, c), and the 2090-2099 time-integrated excess CO_2 flux (OAE minus control run) (b, d). The red contour line represents the region of alkalinity addition.



Results

Lines 389-407: 'OAE-driven impacts on carbonate seasonality are reflected on the seasonal carbon sequestration potential. Both in SSP1-2.6 and SSP3-7.0, it grows over the winter months and decreases over the summer months. The European region is characterised by a much more variable sequestration potential throughout the year, with values ranging between 0.2 and 0.44 (0.26, 0.61) in SSP1-2.6 (SSP3-7.0), while in the coastline region values are more constant, ranging between 0.06 and 0.12 (0.1 and 0.19) in SSP1-2.6 (SSP3-7.0). Additionally, high emissions drive a larger carbon uptake potential, which is related to the scenario-dependent chemical efficiency of OAE whereby, per unit of added alkalinity, higher atmospheric CO_2 concentrations increase the air-sea disequilibrium and decrease the ocean's buffering capacity (Schwinger et al., 2024, Nagwekar et al., 2024, Nagwekar et al., 2026).

When comparing the European region and the coastline region, Figure 7 (a, c) shows that the carbon sequestration potential of OAE is much higher in the former than it is in the latter. This behaviour is explained by the fact that excess carbon uptake is not confined to the place of alkalinity addition, as highlighted in panels (b) and (d). While most additional air-sea CO_2 flux takes place near the coastal shelves, with little increase over the open ocean, this excess downward flux extends beyond the region of alkalinity addition (Palmiéri & Yool, 2024). Furthermore, compared to SSP1-2.6, high emissions strengthen the ocean carbon sink for the same amount of alkalinity addition and within the same spatial extent due to a lower buffer factor in a high-CO_2 world (Nagwekar et al., 2024). '

The Discussion then puts into perspective these findings with the ones from other studies that looked at OAE efficiency:

Lines 482-495: 'With regard to the seasonal carbon sequestration potential, as CO_2 uptake is higher in winter than in summer, efficiency follows the same seasonal trajectory, which seems to contradict previous findings (Zhou et al., 2025, Anderson et al., 2025) that found larger efficiency during summer. However, Zhou et al. (2025) performed pulsed alkalinity addition in various seasons, while Anderson et al. (2025) performed 90-day long simulations where alkalinity is continuously added over winter and over summer. However, pulsed addition is expected to have different outcomes from continuously replenishing the ocean's surface with alkalinity, as is the case of our simulations. In contrast, by simulating continuous OAE over a 10-year simulation in the Bering Strait, Wang et al. (2023) found that warming summer conditions decrease the carbon sequestration potential. Thus, results on efficiency are closely tied to simulation-specific features like the time and rate of alkalinity addition, as well as the definition of efficiency itself. For example, if efficiency is defined in relation to changes to DIC, the type, and resolution, of the model deployed is also relevant, as biogeochemical processes that affect DIC sinks and sources would affect pool estimates.'

Discussion: The discussion repeats in large parts the results and could focus more on interpreting the findings. For example, a main finding is that the seasonal cycle of surface alkalinity is reversed by alkalinity addition (despite the continuous, year-round alkalinity addition), with interesting feedbacks of the other carbon cycle components. Which implications could this have? What does it mean for real world OAE applications if the time of lowest surface pCO2 and the time of the largest amount of additional CO2 uptake are different? Why is this the case? Furthermore, also here it is in parts unclear whether you are talking about the baseline, the OAE simulation, or the difference between both.

Thank you for these suggestions. We acknowledged that the Discussion section should be dedicated more to the interpretation of the results, to also put them in perspective with other studies that looked at similar dynamics. Thus, we largely restructured the section, including a more critical perspective on MRV and ecosystem implications of our findings, as well as highlighting the points of agreement and disagreement with previous research. Please, read below part of the Discussion section where we show an example of how paragraphs have been improved:

Lines 460-470: ‘Multiple studies have investigated the seasonal changes to alkalinity following OAE. In agreement with our results, surface retention of excess alkalinity is better achieved in summer, as shallow, vertically-stratified waters allow for alkalinity not to be lost due to subduction to deeper layers or advection to the open ocean (Wang et al., 2023, Nagwekar et al., 2024, Guo et al., 2025, Wang et al., 2025). Concerning the phase shift of seasonal surface alkalinity, Liu et al. (2025) showed that, by applying OAE to three sites in the southern North Sea, excess MLD-integrated alkalinity seasonality becomes out of face compared to the whole water column, though the peak is detected during winter. Thus, as seasonal shifts to upper alkalinity can vary based on regional features, side changes to the carbonate system and to the local biota would also be site-specific, urging for comprehensive MRV protocols that synthesise signal detectability and ecological risk prevention.’

Lines 471-481: ‘In agreement with Schwinger (2022), OAE in our simulations amplifies the CO_2 seasonal flux under both SSPs, prompting greatest carbon uptake during winter, as OAE is found to amplify the seasonal cycle when highest CO_2 drawdown occurs naturally. Importantly, our results show that increased summer alkalinity leads to the strongest decrease in ocean pCO_2, causing summer conditions to shift from net outgassing to net uptake as a result of rapid air–sea re-equilibration. This effectively turns the European region and the coastline region into year-round CO_2 sinks, while Schwinger (2022) shows that, in their runs, seasonal amplification happens in both directions, therefore increasing outgassing as well as uptake. Additionally, the fact that, in our OAE runs, the CO_2 flux following alkalinity addition remains in phase with MLD seasonality, maintaining largest CO_2 uptake over winter, agrees with Nawgekar et al. (2024), who showed that seasonal shifts of the air-sea CO_2 flux are irrespective of seasonal alkalinity variations. ’

Conclusion: This is rather a summary of the results and a list of limitations (and related recommendations). I would suggest to restructure this part and rather focus on the take-aways and learnings from the study – accepting the limitations – for example regarding real-world applications of OAE including MRV and potential effects on the ecosystem.

Thank you for this input. As you suggested, we moved the limitations paragraph to a dedicated section at the end of the discussion and we emphasised the importance of the main results highlighted in this manuscript, especially with regard to potential side-effects. Following your comments, we highlight the relevance of our results in the context of MRV, for example the reversal of the surface alkalinity seasonal cycle, its potentials for detectability and risk prevention. The new Conclusion section has been added to one of the responses to your comment below.

Line-by-line comments

Abstract

- L. 33-34: “when carbon cycle seasonality is temperature-driven” – I don’t understand this sentence. When is this the case? What if it is not temperature-driven?
Thank you for pointing this out. We agree that the distinction was introduced too abruptly. Thus, we decided to remove this reference, which will be better outlined later in the text. We therefore changed the sentence to:

Lines 31-33: ‘By analysing earth system model simulations of OAE implemented continuously at the European coastline under low and high emissions, it was found that’

Introduction

- L. 68-69: “and eventually stored in the ocean for millennia” – are we sure about this? For example, Köhler (2020)3 reports that the carbon is only sequestered as long as the added alkalinity stays in the ocean. There might be some alkalinity loss, for example by sediment processes. Hence, I suggest to phrase this more cautiously, e.g. “and has the potential to be stored in the ocean for a long time”.
Thank you for your suggestion. We agree that more caution should be used when mentioning long-term storage and changed the text to:

Lines 54-58: ‘One mCDR method under investigation is ocean alkalinity enhancement (OAE), which aims to accelerate the ocean’s CO_2 uptake, as carbon has the potential to be stored in its intermediate and deep waters for a long time. Specifically, OAE would enhance natural weathering, namely the breakdown of rocks and minerals by water-induced chemical reactions that consume atmospheric CO_2’

- L. 81: “DIC leads to CO2 loss” – please check the wording; CO2 is a part of DIC, and “DIC” is not a process.
Thank you for raising this point. The new sentence reads:

Lines 69-71: ‘Conversely, variations in DIC drive CO_2 loss in winter, when enhanced vertical mixing and organic matter respiration increase carbon content at the top layer, and CO_2 uptake in summer, when organic matter production prevails and reduces surface DIC.’

- L. 97: “with potential reflections on marine ecosystems at different scales” – temporal or spatial scales? Statement is a bit unclear.
Thank you for this suggestion. We modified the content of the whole paragraph, and rephrased the sentence to mention relevant changes to the carbonate system. Below you find the new paragraph:

Lines 74-83: ‘OAE could have several impacts on seasonal carbon dynamics, depending on the selected mode and site of alkalinity addition. For example, the rate at which alkalinity is added could produce different magnitudes and timing of CO_2 uptake within the annual cycle, causing asymmetrical or phase shifts to the air-sea CO_2 flux, or altering seasonal extrema. The location of OAE may be affected by the seasonal driver of the air-sea CO_2 flux as well as by physical properties, like bathymetry or regional ocean circulation. Furthermore, adding alkalinity at the surface may surpass critical thresholds, like pH or calcium carbonate saturation, which could in turn affect the ocean's net annual uptake and potentially affect local ecosystems, as other components of the carbonate system would respond accordingly. Lastly, as the ocean pCO_2 seasonal cycle is expected to increase due to rising atmospheric CO_2 concentrations (Gallego et al., 2018), studying the influence of background emissions would help understand the role of different climate mitigation pathways on OAE deployment.'

- L. 93-105: I feel that none of the arguments gives a reasoning why it is important to investigate the seasonality of OAE. Perhaps you can restructure, arguing that despite the continuous addition of the same amount of alkalinity, the surface carbonate system can be affected differently depending on mixed layer etc, which then in turn modifies the CO2 uptake on a seasonal scale (and then give some references – there are some studies which have looked at this already, either with continuous addition or with seasonal/pulsed additions).

Thank you for raising this point. We agree that the arguments for why seasonal dynamics under OAE should be investigated were weak. In addition to adding more information to the previous paragraph, we rephrased and added more content to this paragraph, supporting it with examples from the literature.

Lines 74-97: 'OAE could have several impacts on seasonal carbon dynamics, depending on the selected mode and site of alkalinity addition. For example, the rate at which alkalinity is added could produce different magnitudes and timing of CO_2 uptake within the annual cycle, causing asymmetrical or phase shifts to the air-sea CO_2 flux, or altering seasonal extrema. The location of OAE may be affected by the seasonal driver of the air-sea CO_2 flux as well as by physical properties, like bathymetry or regional ocean circulation. Furthermore, adding alkalinity at the surface may surpass critical thresholds, like pH or calcium carbonate saturation, which could in turn affect the ocean's net annual uptake and potentially affect local ecosystems, as other components of the carbonate system would respond accordingly. Lastly, as the ocean pCO_2 seasonal cycle is expected to increase due to rising atmospheric CO_2 concentrations (Gallego et al., 2018), studying the influence of background emissions would help understand the role of different climate mitigation pathways on OAE deployment.

So far, few studies have investigated the impacts of OAE on the seasonal carbon cycle, mostly at present day conditions. Using a global circulation model, Zhou et al. (2025) simulated pulsed alkalinity addition at different locations and in different seasons, finding that it is generally more efficient to inject alkalinity in summer, as winter mixing quickly removes alkalinity from the ocean surface. Wang et al. (2023) found that, under continuous OAE deployment simulated using a regional ocean model, alkalinity accumulation is largest in summer due to the lower water transport outside the injection site. With a coupled circulation-dissolution model, Wang et al. (2025) studied the detectability and risk exposure of various alkalinity feedstocks, injection locations and seasons of addition, concluding that excess alkalinity is most detectable in summer, when the mean residence time is longest, while the risks of potential negative impacts also increase. However, an analysis that investigates the impacts of continuous coastal OAE deployment on the seasonal carbonate system under different emission pathways has been missing.'

Materials and Methods

- L. 122: "with a horizontal resolution of 1/2°" – is it possible to give the resolution in km in addition? This could be a bit more intuitive.

Thank you for the suggestion. We have added the approximate grid spacing in kilometres. Since the zonal distance of 1/2° longitude depends on latitude, we now provide representative values for southern and northern Europe. We therefore updated the section that introduces the design of the OAE run:

Lines 146-148: 'As the model runs with a horizontal resolution of 1/2°, this corresponds to approximately 55 km in the meridional direction and 45 km zonally in southern Europe, decreasing to about 30 km in northern Europe.'

- L156-157: "equivalent to 1.4 µmol C m-2 y-1" – why in units of carbon?

Thank you for pointing this out. The unit was incorrectly given in carbon units. Since the value refers to added alkalinity, we have removed "C" and now express it as alkalinity equivalents and changed the sentence to:

Lines 148-151: 'OAE is applied from 2025 to 2100, with linear increase over the first decade of addition (2025-2034), until the equivalent of 1 Gt y-1 of fast-reacting calcium hydroxide ($Ca(OH)_2$) is reached. From 2035, this amount, which equals 27 Tmol y-1 of alkalinity (or 44 mol m-2 y-1), is held constant until the end of the century (Figure 1c).'

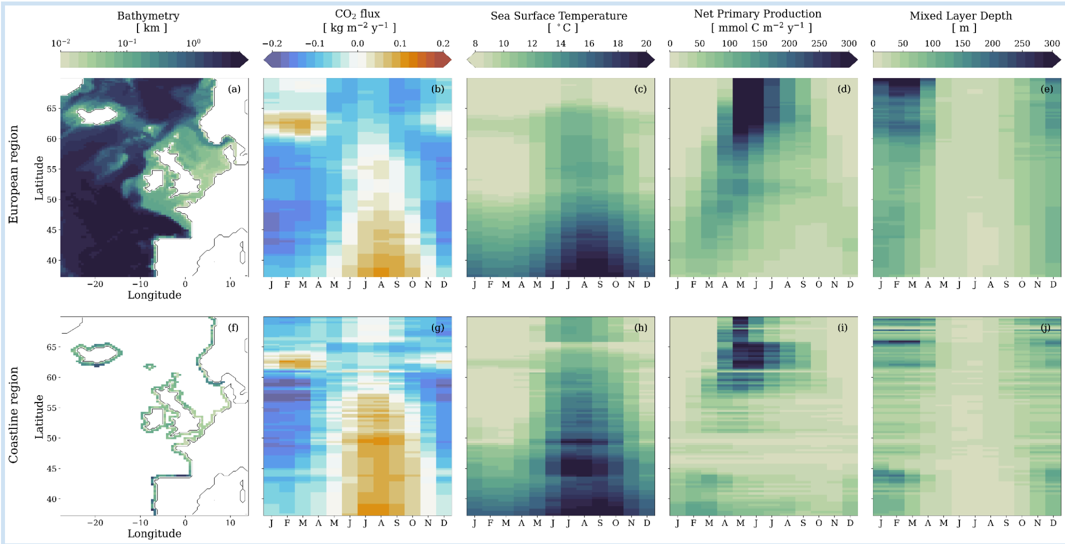
Results

- L. 182-189: "Furthermore, this is the region where the OAE-driven seasonal change is strongest in our model" – as already mentioned before, it is currently unclear to me why you take a closer look at the dynamics of the North Sea? Not sure if the North Sea per se is the region of largest change; looking at Fig. 4a,b,d,e, the change is largest where the bathymetry is shallow, but this could also be the case for other regions in your study area, right? So I would rather link the investigation to the bathymetry rather than a specific region, or link the findings displayed in Fig. 2 more to a plot such as the ones in Fig. 3.

Thank you for your comments. As previously highlighted in earlier responses, we agree that the North Sea section does not fit well within the scope of our manuscript, and we decided to replace this section with one that focuses on the differences between local properties in the European region and in the coastline region. Below, an updated version of Figure 3 is presented with the associated caption and text.

Lines 213-244: 'As a continental shelf pump, the European region plays an important role in carbon uptake by transferring atmospheric CO_2 into interior coastal waters and ultimately to the open ocean in the North Atlantic. As outlined above, the CO_2 flux seasonality is mainly driven by SST, which affects its chemical solubility, and biological processes, whereby carbon is used to sustain photosynthesis. Thus, to provide context for interpreting the results of our OAE runs, we analyse the SSP1-2.6 control seasonal state in the European region (Figure 3a) and in the coastline region.

Lines 220-224: 'Hovmöller diagram of the zonally averaged European region (top) and coastline region (bottom) for bathymetry (a, f), the CO_2 flux (b, g), sea surface temperature (c, h), MLD-integrated net primary production (d, i), and the mixed layer depth (e, j) over the 2090-2099 mean. In the CO_2 flux plot, negative values indicate ocean uptake.'



For the air-sea CO_2 flux, the European region and the coastline region show two opposing biogeochemical geographies. Up to about 60° N, the seasonal carbon cycle is driven by temperature (Figure 3c, h), as the largest ocean CO_2 uptake happens in winter, when CO_2 solubility is strongest, while outgassing takes place in summer, when warmer temperatures inhibit chemical dissolution. Contrarily, between 60° N and 65° N, seasonality is driven by biological productivity: carbon escapes to the atmosphere over the cold months, when NPP is limited by sun and nutrient availability, while, from April to October, increasing productivity consumes CO_2 and ingassing is favoured.

While this pattern is generally homogeneous throughout the two regions, localised divergences emerge. For example, north of 65°, a deeper mixed layer in the European region (Figure 3e) seems to neutralise CO_2 outgassing, while in the coastline region, where the MLD remains relatively shallower (Figure 3j) and SST increases relatively more (Figure 3e), the air-sea CO_2 flux is driven by chemical solubility and the largest CO_2 uptake takes place in winter. This behaviour may be due to the fact that a shallow MLD year-round does not replenish the surface ocean with sub-surface nutrient-rich waters. Additionally, temperature seasonality is stronger in the coastline region than in the European region, especially between 50° N and 60° N, resulting in a relatively more pronounced CO_2 uptake (outgassing) in winter (summer).'

Reference to the coastline bathymetry in the coastline region and MLD in the Results section:

Lines 369-375: 'Importantly, in the OAE runs in both the European region and coastline region, excess surface alkalinity accumulates during summer, prompting a stronger reduction of surface ocean pCO_2 which, due to fast air-sea exchange, turns net summer outgassing into a year-round carbon sink. OAE drives the largest excess CO_2 uptake in winter, as the seasonal air-sea CO_2 flux remains in phase with the MLD cycle, regardless of seasonal variations in alkalinity (Nagwekar et al., 2024). In the coastline region, a shallow bathymetry favours year-round mixing and stronger CO_2 uptake than in the European region.'

Reference to the coastline bathymetry in the coastline region and MLD in the Discussion section:

Lines 435-440: 'In the coastline region, the MLD largely corresponds to the depth of the bathymetry for most of the year (Figure 3), which implies that a shallow, well-mixed compartment may support surface alkalinity retention throughout the year, implying fast air-sea re-equilibration. This finding may however be closely tied to the mode of OAE deployment, that allows the surface ocean to be continuously replenished with alkalinity and drive the disequilibrium between the atmosphere and the ocean.'

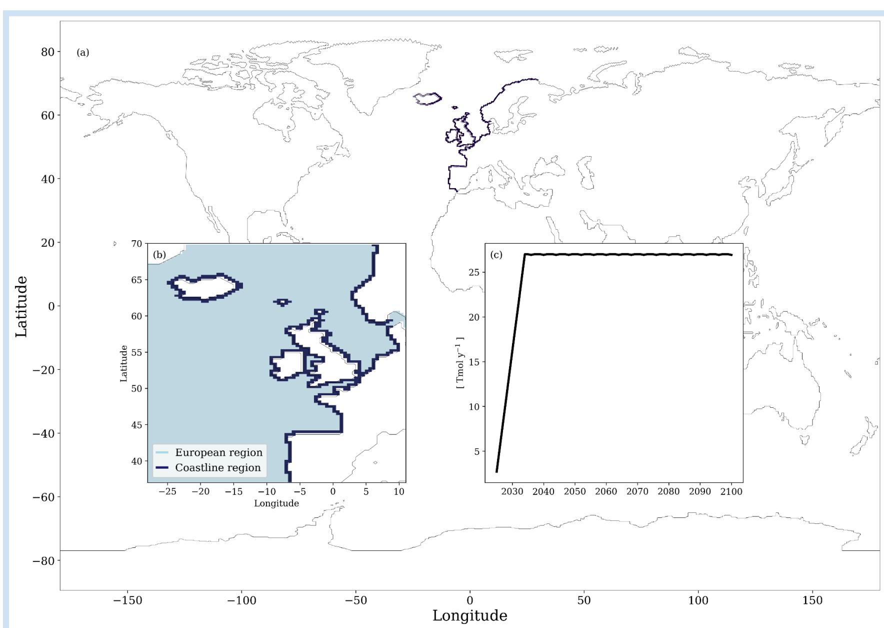
- L. 190: "the seasonal air-sea CO2 flux in the study area"- unclear which "study area"; the North Sea or the red rectangle in Fig. 1?

Thank you for the comment. As you suggested, we decided to confine our analysis to two regions: the European region as a whole and the coastline region. Based on your previous comment, we acknowledged that the term 'study area' is potentially confusing and removed such references in the text, and replaced them consistently with 'European region' and 'coastline region' only.

- L. 207-215: Could you give numbers for the cumulative, area-integrated CO2 flux in the northern and southern North Sea?

Thank you for the suggestion. Given that we decided to drop the analysis on the North Sea, our focus shifted to the comparison between the European region and the coastline region as defined in Figure 1, which has been updated:

Lines 139-143: 'Figure 1: (a) shows the spatial distribution of alkalinity addition along the European coastline (excluding the Mediterranean and the Baltic seas); (b) zooms into the regional domain, highlighting the 'European region' in lightblue and the 'coastline region' in darkblue; (c) shows the time series of coastline alkalinity addition in units of Tmol y-1 from 2025 to 2100.'



- L. 242: "Under both SSPs the MLD-averaged alkalinity spatial pattern" – for the baseline or the OAE simulations?

Thank you for pointing this out. The sentence refers to the OAE runs, which was not clearly stated. We updated the sentence to:

Lines 299-301: ‘Spatially, under both SSPs in the OAE runs, the seasonal amplitude change of MLD-averaged alkalinity reveals strongest variation in the southern North Sea as well as by the UK coastline, where it increases by about 400 μmol kg-1.’

- L. 245: “like Iceland, Spain and Norway” – matter of taste, but I would always talk about the “off the coasts of Iceland, Spain and Norway”, because Iceland, Spain and Norway are not open ocean.

Thank you for the suggestion. We rephrased the sentence to:

Lines 301-304: ‘In SSP3-7.0 (Figure 6c), the seasonal amplitude signal extends over a slightly wider area than in SSP1-2.6 (Figure 6a), while open ocean regions like off the coasts of Iceland, Spain and Norway show less strong changes compared to the control run in SSP1-2.6 and SSP3-7.0.’

- L. 242-246: can you give numbers for the change in MLD (both the seasonal variation and the modification by OAE) in meters? Is it possible to estimate the size of the area (in km2) where the MLD change is largest?

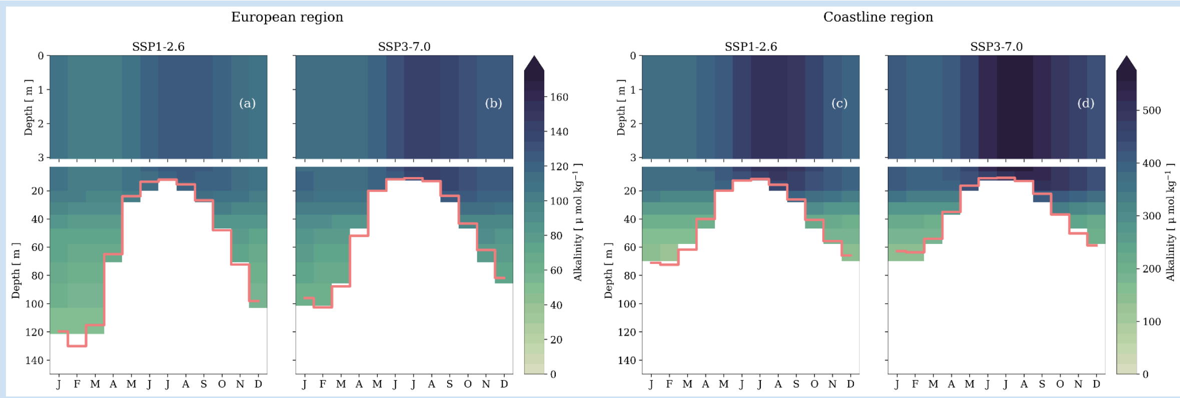
Thank you for this suggestion. We added the MLD seasonal change between the OAE and the control run to Table 1:

Lines 252-256: Table 1: Annual minimum and annual maximum values averaged over 2090-2099 for alkalinity, surface ocean pCO_2, the air-sea CO_2 flux, and the mixed layer depth. Results are presented for the European region and the coastline region under both emission scenarios in the control and OAE runs. Note that air-sea CO2 flux negative values indicate uptake by the ocean.

	European region				Coastline region			
	SSP1-2.6		SSP3-7.0		SSP1-2.6		SSP3-7.0	
	Control	OAE	Control	OAE	Control	OAE	Control	OAE
Alkalinity [μmol kg-1]	(2198, 2210)	(2315, 2327)	(2167, 2184)	(2298, 2314)	(2184, 2203)	(2563, 2672)	(2138, 2162)	(2547, 2685)
Surface ocean pCO2 [μatm]	(404, 433)	(357, 374)	(745, 807)	(674, 719)	(391, 452)	(188, 238)	(730, 836)	(344, 461)
Air-sea CO2 flux [kg m-2 y-1]	(-0.102, 0.009)	(-0.235, -0.067)	(-0.142, 0.038)	(-0.327, -0.053)	(-0.111, 0.03)	(-0.539, -0.209)	(-0.139, 0.061)	(-0.823, -0.318)
Mixed layer depth [m]	(15, 135)	(15, 141)	(14, 107)	(14, 106)	(15, 76)	(15, 75)	(14, 68)	(14, 66)

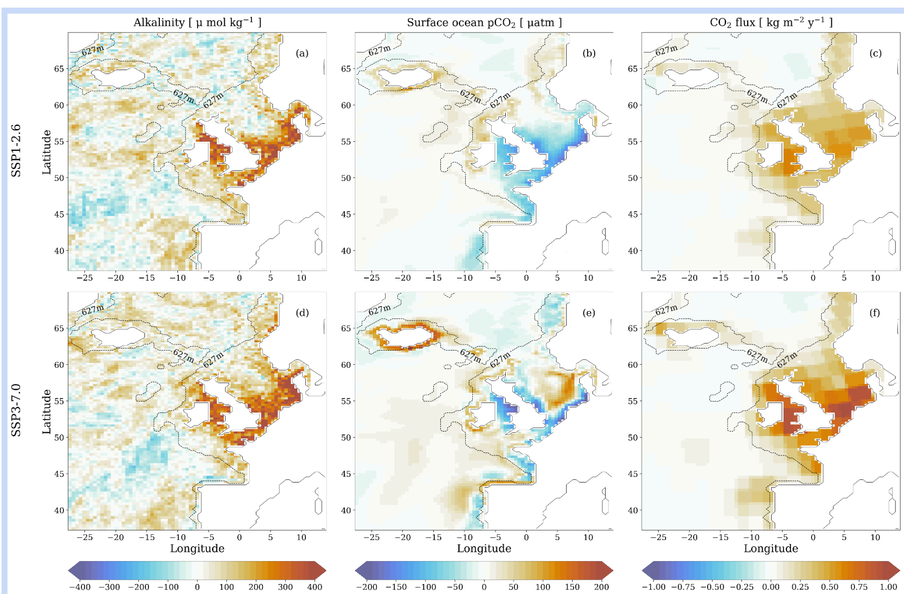
Lastly, we added a figure that shows the MLD change between regions and scenarios:

Lines 294-298: ‘Figure 5: Hovmöller diagram of the zonally averaged alkalinity change (OAE minus control run) as a function of depth over the first model layer (top) and over the mixed layer (bottom). The left panels (a, b) represent the European region and the right panels (c, d) represent the coastline region. The red line corresponds to the mixed layer depth in the control run.’



Lastly, we added a selected 627m isobath to the map to clearly show where largest changes get spatially:

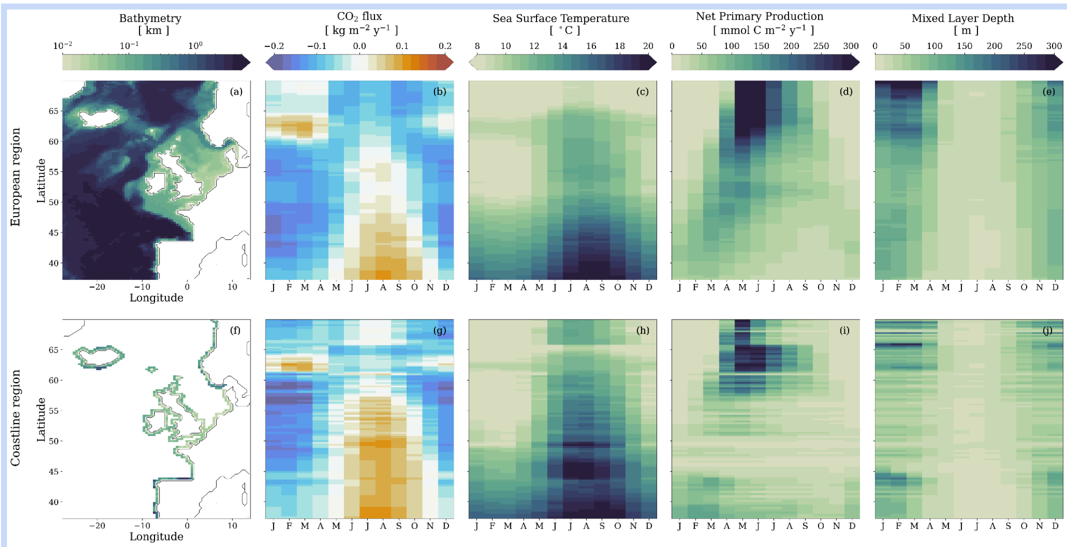
Lines 329-334: ‘Figure 6: Seasonal amplitude change (OAE minus control run) averaged over 2090-2099 for MLD-averaged alkalinity (a, d), for surface ocean pCO_2 (b, e) and for the air-sea CO_2 flux (c, f). The top row shows SSP1-2.6 and the bottom shown is SSP3-7.0. CO_2 flux calculations are performed on the atmospheric component of FOCI, which has a coarser resolution than the ocean component. The dashed line represents the shelf break set at the 627m isobath.’



- L. 249-259: “as a result of phytoplankton bloom and consequent high NPP (fig. 2c)” – the referenced figure is only for the North Sea and not for the entire region though. I suggest to either rephrase the sentence or add a Hovmöller plot for the entire region.

Thank you for the comment. As highlighted above, we decided to replace the North Sea analysis with a comparison between the two regions at focus in this manuscript, namely the European region and the coastline region. Accordingly, below is an updated version of Figure 2:

Lines 222-226: 'Figure 3: Hovmöller diagram of the zonally averaged European region (top) and coastline region (bottom) for bathymetry (a, f), the CO_2 flux (b, g), sea surface temperature (c, h), MLD-integrated net primary production (d, i), and mixed layer depth (e, j) over the 2090-2099 mean. In the CO_2 flux plot, negative values indicate ocean uptake.'



- L. 250-252: "In the OAE simulation, ocean pCO2 absolute values drop and the amplitude decreases from 35 µatm to 23 µatm in SSP1-2.6 and from 73 µatm to 55 µatm in SSP3-7.0." – I don't understand this statement. Yes, pCO2 is decreased with the added alkalinity, but as the seasonal change is, according to your interpretation, caused by NPP, this amplitude would be the same if NPP remains the same, right? Or is there a change in NPP and if yes, why? And if so, which additional effects does this have on the seasonality of the carbonate system?
Thank you for pointing this out. We agree that the statement was unclear. We meant to say that, while in the European region in the control run, lowest pCO2 happens in spring due to NPP, OAE drives a decrease in pCO2 at all seasons, so that spring values remain lowest. As OAE seems to drive higher pCO2 decrease in summer, this consequently drives a decrease in seasonal amplitude, while NPP is not expected to change. We clarified this in the updated text below:

Lines 305-312: 'Looking at surface ocean pCO_2, the European region (Figure 4c, d) is characterised by lowest and highest values of 404 µatm (745 µatm) in May and of 433 µatm (807 µatm) in August under SSP1-2.6 (SSP3-7.0). Minima are registered in spring as a result of phytoplankton bloom and consequent high NPP (Figure 3d), whereby carbon is consumed in photosynthetic fixation. In the OAE run, surface ocean pCO_2 decreases at all seasons and spring values remain lowest, dropping to 374 µatm in SSP1-2.6 and to 674 µatm in SSP3-7.0. The seasonal amplitude decreases from 29 µatm to 17 µatm in SSP1-2.6 and from 64 µatm to 45 µatm in SSP3-7.0, with minimum values still detected over spring.'

- L. 253: "At the coastline" – I suggest to start this paragraph a bit more smoothly, e.g. "While in the European average, pCO2 exhibits the same seasonality in both OAE and baseline simulations, …."
Thank you for this suggestion. We modified the sentence as follows:

Lines 312-314: ‘While in the European region pCO_2 exhibits the same seasonality in both OAE and baseline simulations, in the coastline region, surface ocean pCO_2 is directly influenced by the OAE-driven reversal of the alkalinity seasonal cycle:’

- L. 255: “in the OAE scenario” – I suggest to avoid the term “scenario” if not used in the context of “SSP scenarios”, otherwise this can be confusing. Rather use the term “simulation”.

Thank you for pointing this out. We fully agree with the comment and we changed the term from ‘scenario’ to ‘simulation’ throughout the text when not directly related to SSP scenarios.

- L. 255: “ocean pCO2 decreases by about” – suggest to add the initial value (“decreases from X μatm by about”); same at the end of the sentence (“reduced by 11 μatm”) and in the subsequent sentence.

Thank you for this suggestion. We rephrased the sentence to:

‘Lines 315-318: In SSP1-2.6 (Figure 4c), the seasonal amplitude of the ocean pCO_2 decreases from 61 μatm to 50 μatm, while in SSP3-7.0 (Figure 4d) the amplitude is enhanced from 107 μatm to 116 μatm because OAE drives an even stronger reduction of summer values.’

- L. 259-260: “with the strongest variation occurring in summer” – for coastal or entire European region? Can you give the months in summer that you are referring to?

Thank you for this suggestion. We realised we did not include a clear statement on how we define the individual seasons. We added a dedicated sentence in the Methods section, which reads:

Lines 203-206: ‘In our analysis, we define the “seasonal amplitude” as the difference between the annual maximum and the annual minimum value in a given simulation, and seasons are defined as follows: winter (December, January, February), spring (March, April, May), summer (June, July, August), and autumn (September, October, November)’.

Additionally, we removed the sentence that you highlighted while restructuring the content of the paragraph.

- L. 262-263: “this results in a reduction of the seasonal pCO2 amplitude that is more pronounced under low emissions” – hm, doing the maths using the numbers of two paragraphs before gives me: for SSP1-2.6: 35-23 = 12 μatm, for SSP3-7.0: 73-55= 18 μatm. Hence, the effect on the amplitude is more pronounced under high emissions, isn’t it?

Thanks for this comment. We were referring to the percentage change from the control to the OAE value, hence: (35-23) / 35 = 0.343 versus (73-55) / 73 = 0.247. Thus, we stated that the change is stronger in the lower emission scenario. We also changed some parameters after redoing some calculations, and the sentence has been rephrased:

Lines 319-327: ‘OAE reduces surface ocean pCO_2 in both the European region and in the coastline region, and under both emission scenarios, with the strongest change occurring in summer, when the control runs reach their peak. This indicates that, in our simulations, alkalinity addition produces the greatest pCO_2 decline during periods of naturally high CO_2 outgassing, resulting in a seasonal pCO_2 amplitude damping that is relatively more pronounced under low emissions: in the European region, the seasonal amplitude is reduced by 42% (28%) in SSP1-2.6 (SSP3-7.0); in the coastline region, the amplitude is reduced (enhanced) by 18% (11%) in SSP1-2.6 (SSP3-7.0). The enhanced seasonal amplitude registered in SSP3-7.0 is driven by an even further decrease of pCO_2 summer values.'

- L. 264-267: "Thus, while in a low-warming climate, alkalized water becomes less sensitive to DIC fluctuations, higher atmospheric CO2 partially counteracts the buffering effect driven by alkalinity addition, leading to a higher Revelle factor." – yes, but this is common sense, isn't it? Or what is your specific finding in terms of seasonality? Furthermore, I suggest to be more careful with statements about the Revelle factor; if you haven't looked at it (maybe not written as an output?) you can only speculate.
Thank you for your comments here. We realised that this statement was ambiguous and decided to remove it, together with references to the Revelle factors that may be speculative if not backed by figures.

- L. 277: "a distinct spatial pattern of pCO2 seasonal change is identified" – add that this is caused by OAE.
Thank you for the suggestion. We changed the sentence to:

Lines 335-336: 'In the SSP1-2.6 scenario (Figure 6b), a distinct spatial pattern of pCO_2 seasonal amplitude change driven by OAE is identified:'

- L. 288-289: "Alkalinity addition enhances the CO2 flux seasonal cycle everywhere" – that sounds as if also outgassing in summer is enhanced; is this the case?
Thank you for raising this point. We see how this sentence was phrased incorrectly. We meant to say that alkalinity enhances the downward CO2 flux at all times. We rephrased the sentence to:

Lines 358-363: 'In the European region, with OAE deployment the ocean's CO_2 uptake potential is enhanced at all seasons: it ranges from 0.235 (0.327) kg CO_2 m-2 yr-1 in winter to 0.076 (0.053) kg CO_2 m-2 yr-1 in summer under SSP1-2.6 (SSP3-7.0). As OAE drives largest uptake during winter, it enhances the seasonal CO_2 flux, with a new amplitude of 0.168 kg m-2 yr-1 in SSP1-2.6 and 0.292 kg m-2 yr-1 in SSP3-7.0, compared to their respective controls (0.111 kg m-2 yr-1 and 0.18 kg m-2 yr-1). '

- L. 289-290: "turning the system into a CO2 sink year-round" – this sounds like an interesting and relevant finding that could be highlighted more.
Thank you for this remark. As highlighted earlier, we added this finding to key point two and we discussed this further in the Discussion section:

Lines 369-376: 'Importantly, in the OAE runs, excess surface alkalinity accumulates during summer, prompting a stronger reduction of surface ocean pCO_2 which, due to fast air-sea exchange, turns net summer outgassing into a year-round carbon sink. OAE drives the largest excess CO_2 uptake in winter, as the seasonal air-sea CO_2 flux remains in phase with the MLD cycle, regardless of seasonal variations in alkalinity (Nagwekar et al., 2024). As for the role of the emission scenario, SSP3-7.0 drives an even stronger carbon uptake in winter, while maintaining summer values similar to SSP1-2.6, which further increases the CO_2 flux seasonal amplitude. As it will be described later, this behaviour is due to the lowering buffering capacity of the ocean under higher emissions. '

Lines 425-431: 'In the coastline region, this phase shift of surface alkalinity drives the reversal of ocean pCO_2 seasonality, though the CO_2 uptake, and the OAE-driven uptake increase, remains largest during winter, as CO_2 seasonality follows MLD seasonality. This leads to two main conclusions: one the one hand, increasing ocean disequilibrium with the overlying atmosphere turns summer net outgassing into net uptake year-round due to fast air-sea exchange; on the other hand, as the system moves to colder months, SST decreases, the MLD deepens and CO_2 dissolution is favoured'

- L. 286-292: This entire paragraph would benefit from numbers which help the reader to understand the magnitudes of the impact.

Thank you for suggesting this. We saw how more quantitative elements could give more clarity to the text. Here's the revised paragraph:

Lines 350-368: 'As for the CO_2 flux, seasonality is overall driven by temperature in our domain: the system outgasses (takes up) CO_2 in summer (winter), at lowest (highest) chemical solubility, and the largest CO_2 release happens between July and August. This pattern follows MLD seasonality, whereby summer warming shoals the mixed layer, reducing CO_2 uptake, and winter mixing deepens the mixed layer, enhancing the CO_2 flux. Under SSP1-2.6, the European region ranges from an uptake of 0.102 kg CO_2 m-2 y-1 between December and January and an outgassing of 0.009 kg CO_2 m-2 y-1 between July and August, while in SSP3-7.0, values are slightly more extreme: 0.142 kg m-2 y-1 CO_2 in winter and 0.038 kg m-2 y-1 CO_2 in summer.

In the European region, with OAE deployment the ocean's CO_2 uptake potential is enhanced at all seasons: it ranges from 0.235 (0.327) kg CO_2 m-2 yr-1 in winter to 0.076 (0.053) kg CO_2 m-2 yr-1 in summer under SSP1-2.6 (SSP3-7.0). As OAE drives largest uptake during winter, it enhances the seasonal CO_2 flux, with a new amplitude of 0.168 kg m-2 yr-1 in SSP1-2.6 and 0.292 kg m-2 yr-1 in SSP3-7.0, compared to their respective controls (0.111 kg m-2 yr-1 and 0.18 kg m-2 yr-1). This results in a seasonal amplification by 51% and by 62% in the low- and high-emission scenario, respectively. In the coastline region, the seasonal amplification signal is larger than in the European region: the CO_2 flux seasonal amplitude is 0.329 kg m-2 yr-1, therefore more than doubling the amplitude in the control run, which amounts to 0.114 kg m-2 yr-1. With an amplitude of 0.505 kg m-2 yr-1, the OAE seasonal CO_2 flux in SSP3-7.0 is more than 2.5 times larger than the control (0.199 kg m-2 yr-1).'

- L 293: "OAE-induced CO2 flux amplitude has an average span of" – can't you simply say that the effect of OAE on the seasonal CO2 flux is XYZ?

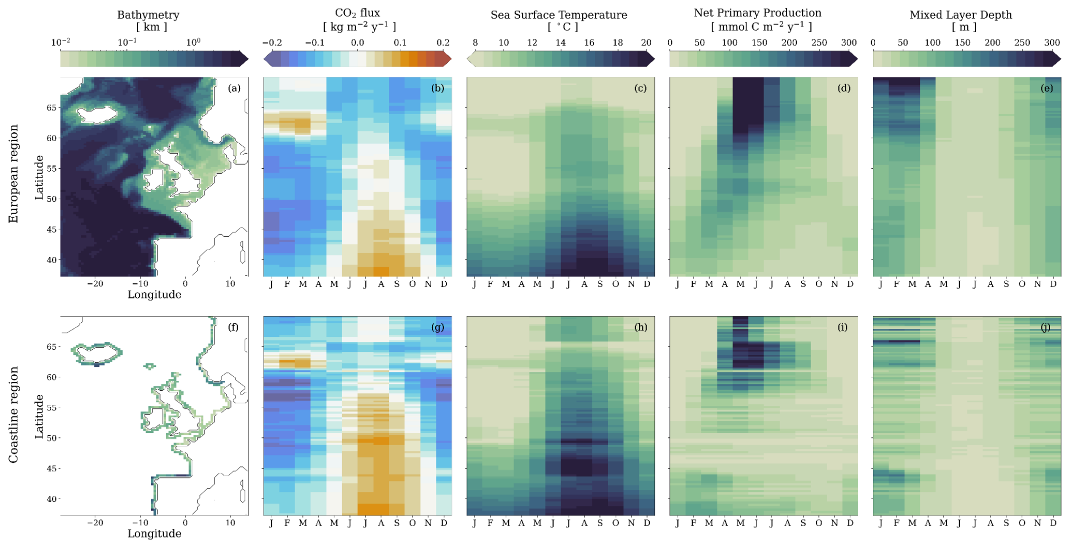
Thank you for the suggestion. This phrasing was complicating its actual meaning. We rephrased large part of the paragraph:

Lines 358-363: 'In the European region, with OAE deployment the ocean's CO_2 uptake potential is enhanced at all seasons: it ranges from 0.235 (0.327) kg CO_2 m-2 yr-1 in winter to 0.076 (0.053) kg CO_2 m-2 yr-1 in summer under SSP1-2.6 (SSP3-7.0). As OAE drives largest uptake during winter, it enhances the seasonal CO_2 flux, with a new amplitude of 0.168 kg m-2 yr-1 in SSP1-2.6 and 0.292 kg m-2 yr-1 in SSP3-7.0, compared to their respective controls (0.111 kg m-2 yr-1 and 0.18 kg m-2 yr-1).'

- Fig. 2c: Does it make a difference if you look at depth-integrated NPP? I don't know your model, but considering the entire euphotic zone can sometimes change the picture of spatial NPP patterns compared to surface-only values.

Thank you for the suggestion. We agree that MLD-integrated NPP is more appropriate. We updated the figure and see that the pattern seems to largely remain the same, with highest biological activity at northern latitudes in spring and summer.

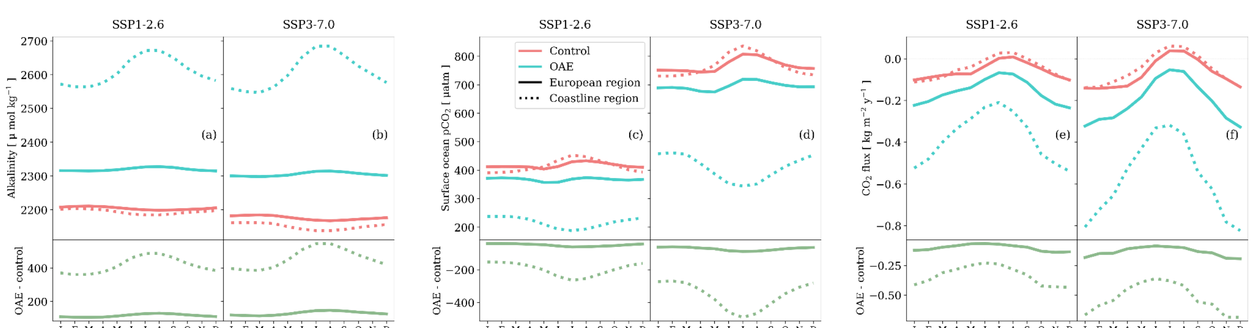
Lines 222-226: ‘Figure 3: Hovmöller diagram of the zonally averaged European region (top) and coastline region (bottom) for bathymetry (a, f), the CO_2 flux (b, g), sea surface temperature (c, h), MLD-integrated net primary production (d, i), and the mixed layer depth (e, j) over the 2090-2099 mean. In the CO_2 flux plot, negative values indicate ocean uptake.’



- Fig. 3 caption: “ocean pCO2” – change to “surface ocean pCO2”

Thank you for suggesting this. We updated the figure’s caption as well as the variable’s name in figure 4.

LInes 267-273: ‘Figure 4: Seasonal cycle averaged over 2090-2099 for surface alkalinity in SSP1-2.6 (a) and in SSP3-7.0 (b), for surface ocean pCO_2 in SSP1-2.6 (c) and in SSP3-7.0 (d), and for the CO_2 flux in SSP1-2.6 (e) and in SSP3-7.0 (f), with the respective difference depicted by the green line and the difference of the mixed layer depth depicted by the yellow line. Continuous lines represent the European region and dashed lines represent the coastline region. In the CO_2 flux plots, negative values indicate ocean uptake.’



- Fig. 4 caption: "Seasonal amplitude change (OAE – baseline)" – I'm not sure if I understood the computation entirely. Could you add this either in more detail to the caption or as a short paragraph to the methods?
Thank you for pointing it out. We realised we didn't include a clear definition of seasonal amplitude in the manuscript. An additional paragraph has been added to the Data processing sub-section in the Methods section:

Lines 203-206: 'In our analysis, we define the "seasonal amplitude" as the difference between the annual maximum and the annual minimum value in a given simulation, and seasons are defined as follows: winter (December, January, February), spring (March, April, May), summer (June, July, August), and autumn (September, October, November)'.

Additionally, we updated the caption in the figure to:

Lines 329-333: 'Figure 6: Seasonal amplitude change (OAE minus control run) averaged over 2090-2099 for MLD-averaged alkalinity (a, d), for surface ocean pCO_2 (b, e) and for the air-sea CO_2 flux (c, f). The top row shows SSP1-2.6 and the bottom shown is SSP3-7.0. CO_2 flux calculations are performed on the atmospheric component of FOCI, which has a coarser resolution than the ocean component. The dashed line represents the shelf break set at the 627m isobath.'

Discussion

- L. 307-312: I suggest to move this part to the end of the discussion in a dedicated "limitations" paragraph.
Thank you for the suggestion. We added the paragraph to a dedicated Limitations section, where we also highlight the limitations presented in the conclusion. Here's the Limitations section:

Lines 532-536: 'Lastly, this manuscript does not address alkalised water that is subducted before air-sea equilibration is complete, and uncertainty remains on whether that water could resurface to drive CO_2 uptake elsewhere. In Palmiéri & Yool (2024), for example, it was estimated that about 50% of CO_2 uptake favoured by global coastal OAE happened remotely from the alkalinity injection sites, as it is partially reflected in Figure 7.'

- L. 313: "In agreement with Schwinger (2022)" – this statement is true for both scenarios, right? I suggest to add this to the sentence.
Thank you for suggesting this. We updated the sentence to:

Lines 462-464: 'In agreement with Schwinger (2022), OAE in our simulations amplifies the CO_2 seasonal flux under both SSPs, prompting greatest carbon uptake during winter, as OAE is found to amplify the seasonal cycle when highest CO_2 drawdown occurs naturally.'

- L. 313-321: I think this paragraph needs more discussion. You repeat your findings, but it is still unclear to me how the lowered surface pCO2 in summer and the increased CO2 flux in winter fit into the same picture. I think the carbonate system responses need to be clearly described, perhaps a schematic would help. Furthermore, it should also be discussed with regard to previous studies that were looking at seasonal OAE effects.

Thank you for the comment. We understand that these concepts have not been clearly described. We added some clarifications on how CO2 flux and pCO2 fit in the same picture and on how to this compares to previous studies:

Lines 475-485: 'In agreement with Schwinger (2022), OAE in our simulations amplifies the CO_2 seasonal flux, prompting greatest carbon uptake during winter, as OAE is found to amplify the seasonal cycle when highest CO_2 drawdown occurs naturally. Importantly, our results show that increased summer alkalinity leads to the strongest decrease in ocean pCO_2, causing summer conditions to shift from net outgassing to net uptake as a result of rapid air–sea re-equilibration. This effectively turns the European region and the coastline region into year-round CO_2 sinks, while Schwinger (2022) shows that, in their runs, seasonal amplification happens in both directions, therefore increasing outgassing as well as uptake. Additionally, the fact that, in our OAE runs, the CO_2 flux following alkalinity addition remains in phase with MLD seasonality, maintaining largest CO_2 uptake over winter, agrees with Nawgekar et al. (2024), who showed that seasonal shifts of the air-sea CO_2 flux are irrespective of seasonal alkalinity variations.'

- L. 315-316: "Additionally, OAE-induced modifications to ocean pCO2 are highest" – I suggest to rephrase to "Additionally, OAE-induced reductions of surface ocean pCO2 are largest"

Thank you for this suggestion. Following your comments, we substantially restructured the Discussion section, which is now more focused on the relevance of the main results and how they compare with other studies. Thus, the sentence has been removed.

- L. 322: "Both in European waters and at the coastline, highest alkalinity is recorded" – in the baseline or the OAE simulations?

Thank you for this point. The same response from the previous comment applies here. As we substantially restructured the Discussion section, the sentence has been removed.

- L. 326-328: "Considering the physical features of the southern NS, where a shallow water column is well-mixed throughout the year, OAE is likely to encourage fast equilibration and allow for efficient carbon sequestration under enhanced alkalinity." – okay, but what about the remaining North Sea and the rest of the European region?

Thank you for pointing this out. This lack of clarity was addressed by removing the North Sea section and focusing solely on the comparison between the European region and the coastline region as defined by the updated figure 1. This is the text where we explain the different dynamics between the European region and the coastline region.

Lines 427-440: 'Secondly, continuous OAE deployment induces surface ocean pCO_2 reduction at all seasons, but most strongly when the associated seasonal driver reduces the ocean CO_2 sink potential, which is summer in the temperature-driven European region. In the coastline region, this phase shift of surface alkalinity drives the reversal of ocean pCO_2 seasonality, though the CO_2 uptake, and the OAE-driven uptake increase, remains largest during winter, as CO_2 seasonality follows MLD seasonality. This leads to two main conclusions: one the one hand, increasing ocean disequilibrium with the overlying atmosphere turns summer net outgassing into net uptake year-round due to fast air-sea exchange; on the other hand, as the system moves to colder months, SST decreases, the MLD deepens and CO_2 dissolution is favoured. In the coastline region, the MLD largely corresponds to the depth of the bathymetry for most of the year (Figure 3), which implies that a shallow, well-mixed compartment may support surface alkalinity retention throughout the year, implying fast air-sea re-equilibration. This finding may however be closely tied to the mode of OAE deployment, that allows the surface ocean to be continuously replenished with alkalinity and drive the disequilibrium between the atmosphere and the ocean.'

- L. 330: "In the OAE simulations, the seasonal cycle of surface alkalinity is reversed under both SSPs, especially in summer" – I would continue this sentence with a reason why this is the case and speculate which effects this could have on biogeochemistry and ecology.

Thank you for the suggestion. We added more details to the paragraph, highlighting the relevance of this finding in the context of MRV as well as risks to local ecosystems.

Lines 414-426: 'This study provides an assessment of OAE-driven impacts on the seasonal carbonate system. OAE was simulated as a continuous surface alkalinity injection to a coastal strip in the European coastline, under low and high emissions. This formulation allowed us to investigate the location- and scenario-dependency of OAE effects, drawing some key findings. First, adding alkalinity at the surface reverses its seasonal cycle, as temperature-induced vertical stratification in summer retains excess alkalinity at the top, while dilution with low alkalinity sub-surface water is favoured in winter. This outcome is especially relevant in the context of monitoring, reporting and verification (MRV) protocols, as measuring seasonal shifts could be an opportunity to quantify metrics on OAE detectability. At the same time, surface alkalinity in the coastal region increases by more than 500 μmol kg-1 during summer, potentially exceeding critical thresholds for parameters such as pH and aragonite saturation state, thereby adversely affecting local biota. Potential negative side-effects could be partially mitigated by choosing the optimal alkalinity feedstock tailored to the time, rate and place of addition (Wang et al., 2025).'

- L. 332-333: "show a less significant decline" – I suggest to avoid the term "significant" if not used in a statistical context.

Thank you for pointing this out. As the Discussion section was largely modified, the piece of text has been removed and all the other sentences that included 'significant' have been reworded.

- L. 333-336: "the amplitude compression signal", "the SSP3-7.0 coastal amplitude", "the seasonal amplification" – these are a variety of terms that might all be used in a similar sense. I suggest to create certain terms for a particular OAE-induced change in the carbonate system seasonality and use them consistently throughout. If it is too difficult to describe in words which amplitude is changed into which direction, you could accompany the term definition with a simple schematic.

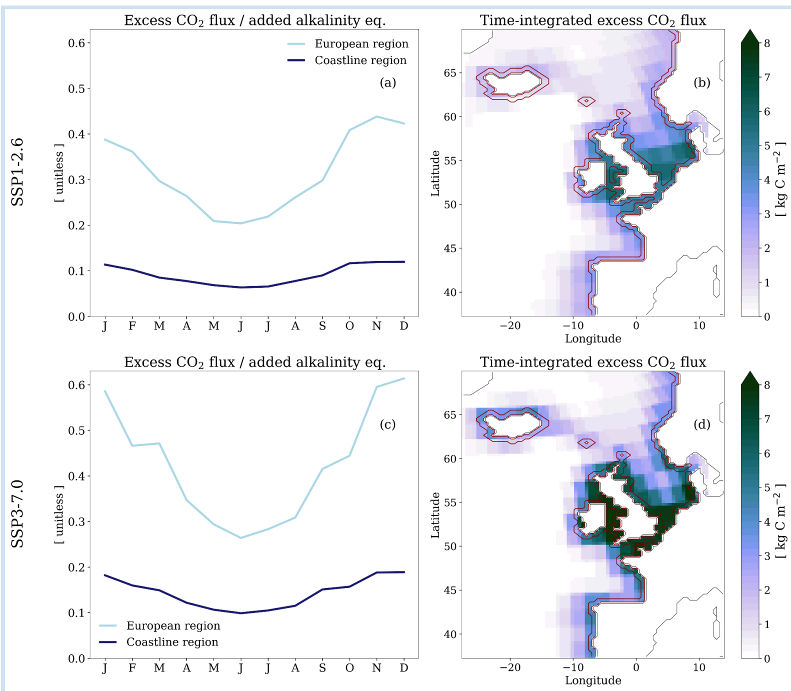
Many thank you for the suggestion. We fully agree that terminology needs to be used consistently throughout the text. We decided to not include a schematic in order to not overload the manuscript with figures but we adapted the manuscript to a less complicated and more consistent wording. We made some consistent changes, such as: using only 'European region' and 'coastline region' to refer to the two regions considered in the manuscript. Additionally, we changed the text to 'amplitude increase / enhanced' and 'amplitude decrease / reduced / dampened'.

- L. 336-337: "For the CO2 flux, since the seasonal amplification is stronger in SSP 3-7.0, higher background emissions make the system more susceptible to external alterations" – isn't the argumentation the other way around? Because of higher emissions the sensitivity and, thus, the seasonal amplitude is stronger.

Thank you for pointing this out. The sentence was over-complicating the concept we wanted to elaborate. We clarified that higher emissions mean more CO2 flux into the ocean and more efficiency as per a new figure 7. We updated the entire paragraph and rephrased to:

Lines 371-378: 'Importantly, in the OAE runs, excess surface alkalinity accumulates during summer, prompting a stronger reduction of surface ocean pCO_2 which, due to fast air-sea exchange, turns net summer outgassing into a year-round carbon sink. OAE drives the largest excess CO_2 uptake in winter, as the seasonal air-sea CO_2 flux remains in phase with the MLD cycle, regardless of seasonal variations in alkalinity (Nagwekar et al., 2024). As for the role of the emission scenario, SSP3-7.0 drives an even stronger carbon uptake in winter, while maintaining summer values similar to SSP1-2.6, which further increases the CO_2 flux seasonal amplitude. As it will be described later, this behaviour is due to the lowering buffering capacity of the ocean under higher emissions.'

Lines 386-390: 'Figure 7: The seasonal carbon sequestration potential defined as the ratio between the change in CO_2 flux and the added alkalinity carbon equivalent averaged over 2090-2099 (a, c), and the 2090-2099 time-integrated excess CO_2 flux (OAE minus control run) (b, d). The red contour line represents the region of alkalinity addition.'



Lines 406-411: 'While most additional air-sea CO_2 flux takes place near the coastal shelves, with little increase over the open ocean, this excess downward flux extends beyond the region of alkalinity addition (Palmiéri & Yool, 2024). Furthermore, compared to SSP1-2.6, high emissions strengthen the ocean carbon sink for the same amount of alkalinity addition and within the same spatial extent due to a lower buffer factor in a high-CO_2 world (Nagwekar et al., 2024).'

- L. 348-349: "OAE alone is less efficient in mitigating seasonal amplitude changes in the high- emissions scenario compared to the low-emission scenario" – you lost me here (and in the following sentences). The purpose of OAE is not to modify any seasonal signal; and I'm a bit confused about the direction of changes. Again, perhaps a schematic or summary figure could help. And a small note: check to be consistent, use either "high-emissions scenario" (with s) or "high-emission scenario" (without s).

Thank you for your comments. Starting from your last point, we consistently used 'high-' and 'low-emission scenario' throughout the text. Additionally, as per your first point, the term 'mitigating' is incorrectly used in these sentences, as we intended to state that OAE is less efficient in *dampening* the seasonal amplitude of ocean pCO2. As we restructured the whole paragraph, this is the new sentence that refers to this mechanism:

Lines 500-511: 'Lastly, we investigate the role of the background scenario on OAE impacts. In our simulations the ocean's carbon sink is increased more strongly in SSP3-7.0 than in SSP1-2.6, as surface alkalinity reaches similar levels in the two scenarios (Figure 3a, b) but surface DIC increases more under high emissions (not shown). This finding agrees with Schwinger et al. (2024), who showed that increasing emissions drive an even further ocean uptake of anthropogenic CO_2 compared to a non-transient OAE simulation, due to elevated surface DIC concentrations and a decreasing buffering capacity of the ocean. Similarly, Nagwekar et al. (2026) found that, in SSP3-7.0, a higher air-sea partial pressure difference compared to SSP1-2.6 increases the size of the carbonate system response to alkalinity addition, driving larger additional CO_2 uptake. This same result was previously highlighted by Nagwekar et al. (2024), where OAE efficiency was higher in SSP3-7.0 (compared to SSP1-2.6) due to higher background atmospheric CO_2 and, most importantly, due to a decreasing buffer factor.'

- L. 351-352: "an overall expansion of the CO2 seasonal cycle" – expansion spatially, temporarily, stronger amplitude? This is currently unclear.

Thank you for this comment. This and the previous one helped us acknowledge that terminology was partially inconsistent within the text. This is how the sentence has been rephrased.

Lines 500-506: 'Lastly, we investigate the role of the background scenario on OAE impacts. In our simulations the ocean's carbon sink is increased more strongly in SSP3-7.0 than in SSP1-2.6, as surface alkalinity reaches similar levels in the two scenarios (Figure 3a, b) but surface DIC increases more under high emissions (not shown). This finding agrees with Schwinger et al. (2024), who showed that increasing emissions drive an even further ocean uptake of anthropogenic CO_2 compared to a non-transient OAE simulation, due to elevated surface DIC concentrations and a decreasing buffering capacity of the ocean.'

Conclusions

- L. 358: "under low and high warming" – this comment might be a bit picky, but the warming is secondary, the main driver of the scenarios is actually the change in emissions. The warming then depends on the model-specific sensitivities. So I would talk about "high and low-emission scenarios".

Thank you for pointing it out. Yes, we fully agree that emissions, rather than mentioning the warming, is the first-order classification of SSP scenarios. We thus rephrased the sentence:

Lines 539-541: 'The present study addressed the changes to the seasonal carbon cycle driven by coastal OAE application under a low- and high-emission scenario, contributing to the understanding of OAE-driven CO_2 intra-annual variability in a continental shelf.'

- L. 362-364: "the sensitivity of the seasonal carbon cycle increases under high emissions, enhancing the CO2 flux seasonal amplification and contrasting the pCO2 seasonal dampening" – I suggest to rephrase to "the sensitivity of the seasonal carbon cycle increases under high emissions, enhancing the OAE-driven excess CO2 uptake in winter and dampening the OAE-driven reduction in surface ocean pCO2."
Thank you for this point. As we largely changed the structure of this section, this sentence has been removed.

- L. 368-381: I would suggest to move this into a dedicated limitations paragraph at the end of the discussion rather than adding this to the conclusion. You summarize what you could have done better (and there are always things to improve), but in a conclusion you should rather talk about potential next steps that could follow building on your scientific findings.
Thank you for this suggestion. We moved this paragraph into a dedicated Limitations section at the end of the discussion and largely restructured the Conclusion section:

Lines 539-554: 'The present study addressed the changes to the seasonal carbon cycle driven by coastal OAE application under a low- and high-emission scenario, contributing to the understanding of OAE-driven CO_2 intra-annual variability in a continental shelf. It was found that, when addition takes place at the top layer, excess alkalinity accumulates more strongly in summer, as a shallow mixed layer retains alkalised water at the surface. This has the consequence of reversing, as well as amplifying, the seasonal cycle of surface alkalinity. Additionally, OAE reduces ocean pCO_2 more strongly in summer, when it is naturally highest, which, thanks to fast air-sea re-equilibration, turns summer net CO_2 outgassing into CO_2 net uptake year-round. However, OAE drives the strongest CO_2 uptake change in winter, when it is naturally strongest, as air-sea CO_2 flux remains in phase with the MLD seasonal cycle. While the design of our OAE runs mimics an idealised application, which is unlikely to become a real-world case, coastal OAE implementation is expected to become one of the more feasible approaches, due to proximity with existing coastal infrastructures. Nevertheless, such interventions could create additional pressures on local communities and ecosystems. Thus, drawing from the results highlighted in this study, other coastal methods like pulsed or point-source experiments should be explored to ensure safe large-scale OAE deployment.'

- L. 372: "Additionally, as river runoff features are deeply seasonal…" – is deeply the correct word here? Shouldn't it be rather something like "has a strong seasonality"?
Thank you for the suggestion. As per your suggestion, a new Limitations section has been added, where this sentence was rephrased:

Lines 525-527: 'Furthermore, while freshwater input from rivers is modelled in FOCI, riverine alkalinity is not accounted for. As river runoff has a strong seasonality, implementing such processes would improve the accuracy of future OAE simulations'.

- L. 377-379: "Lastly, our OAE simulations picture a highly idealized scenario, which is unlikely to become a real-world case." – yes, but this is actually the case for almost all past and current OAE modelling studies, right? But we can still learn from it – I suggest to rephrase this sentence to admit the simplifications but highlight the value of the study.
Thank you for the comment. We modified the sentence, which now reads:

Lines 548-554: ’While the design of our OAE runs mimics an idealised application, which is unlikely to become a real-world case, coastal OAE implementation is expected to become one of the more feasible approaches, due to proximity with existing coastal infrastructures. Nevertheless, such interventions could create additional pressures on local communities and ecosystems. Thus, drawing from the results highlighted in this study, other coastal methods like pulsed or point-source experiments should be explored to ensure safe large-scale OAE deployment.’