

REVIEWER 1

Ciscato et al.: „Impact of simulated coastal ocean alkalinity enhancement on the seasonal cycle of the air-sea CO₂ flux and surface ocean pCO₂ 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 CO₂ uptake mainly in winter and lowers the surface ocean pCO₂ 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 CO₂ 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 CO₂ 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 pCO₂ and enhanced CO₂ 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 pCO₂ change and changes to the air-sea CO₂ flux, stressing the outcome that the European region shifts 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 set-up 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 numeric values to the Results section, which are also illustrated in the new 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 CO₂ flux and surface ocean pCO₂” 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 CO₂ uptake, which is key of OAE? I.e., does it matter that surface pCO₂ is lowered in summer but CO₂ 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-CO₂ 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 CO₂ uptake?

Thank you for the comments. Regarding the second point in the key points, we agree that the statement sounds confusing. 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 CO₂ 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 15-20:

- Ocean Alkalinity Enhancement (OAE) aims to increase the ocean’s potential to sequester and store atmospheric CO₂
- Due to summer retention, surface OAE reverses the seasonal cycle of alkalinity and it decreases ocean pCO₂, turning the system into a year-round carbon sink

- OAE drives the strongest CO₂ uptake enhancement in winter, while high emissions amplify this signal

Lines 31-40:

One potentially scalable method to remove CO₂ from the air is ocean alkalinity enhancement (OAE), which works to lower its sea surface partial pressure (pCO₂) and accelerate CO₂ 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 CO₂ 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 pCO₂ most strongly in summer, turning the region into a year-round carbon sink; b) the strongest air-sea CO₂ uptake enhancement 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 42-48: 'Ocean Alkalinity Enhancement (OAE) is a marine 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 emissions. We found that stratification retains higher alkalinity over summer, reducing the ocean pCO₂ and turning the region into a year-round carbon sink. Additionally, high emissions lower the ocean's buffering capacity and increase winter CO₂ uptake'.

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 Fig. 1 in a later response), and drop the North Sea analysis. This is how we made this clear in the text:

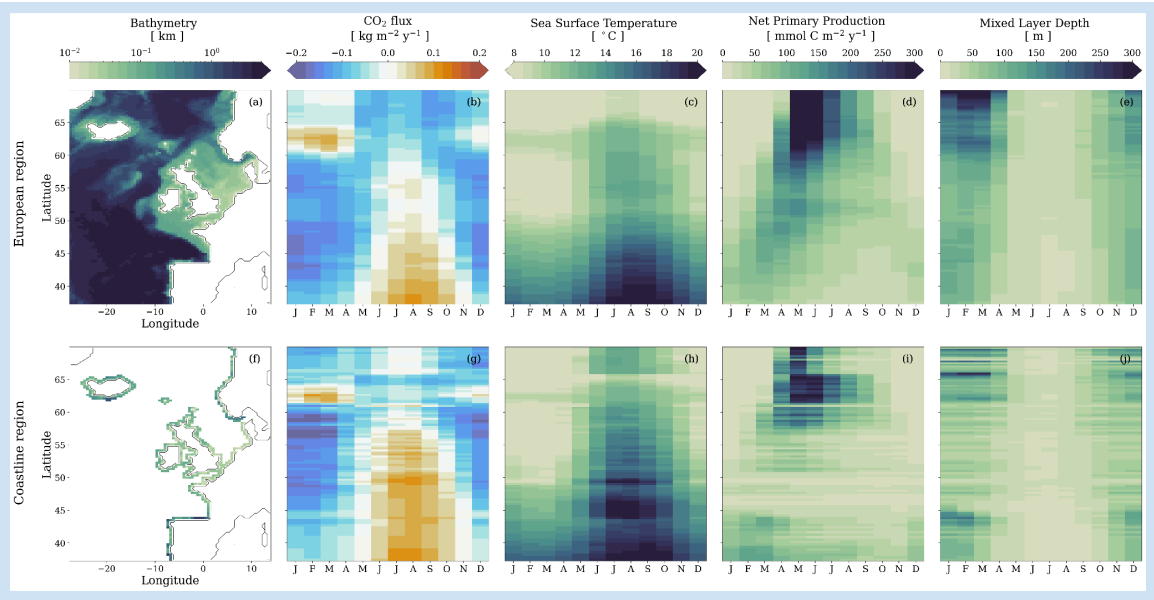
Lines 190-196: 'Our analysis focuses on the comparison between two regions: the 'coastline region', which corresponds to the shelf grid cells highlighted by the dark blue line in Fig. 1b, offers details on regime shifts that take place at the epicenter of the domain; the 'European region', which corresponds to the coloured ocean region in Fig. 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 our research questions, we decided to replace this section with a comparison between the European region and the coastline region. We thus updated Fig. 3 accordingly:

Lines 225-229: ‘Figure 3: Hovmöller diagram of the zonally averaged European region (top) and coastline region (bottom) for bathymetry (a, f), the CO₂ 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 CO₂ 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.

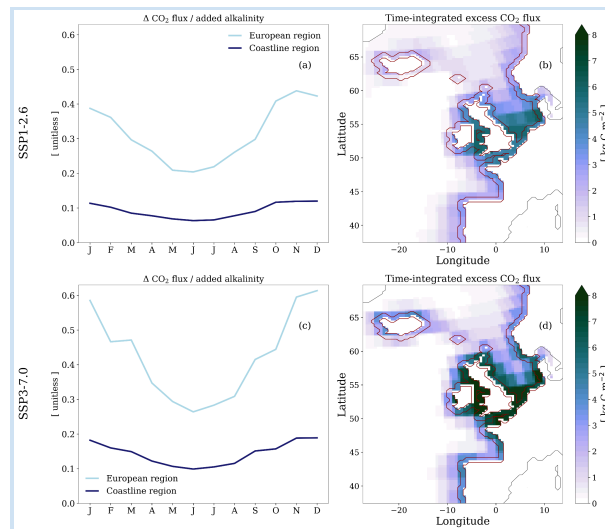
Lines 255-259: ‘Table 1: Annual minimum and annual maximum values averaged over 2090-2099 for alkalinity, surface ocean pCO₂, the air-sea CO₂ flux, and the mixed layer depth. Results are presented for the European region and the coastline region under both emission scenarios in the control and OAE runs. 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 pCO ₂ [μatm]	(404, 433)	(357, 374)	(745, 807)	(674, 719)	(391, 452)	(188, 238)	(730, 836)	(344, 461)
Air-sea CO ₂ 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)

Additionally, we added numerical values to the text in the Results section, as it will be highlighted in later responses.

Concerning efficiency, we consciously decided to not focus on that in this manuscript, as we thought that this would have slightly shifted the focus of our paper on seasonal changes. Additionally, another paper is being drafted at the moment with more 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 389-393: ‘Figure 7: The seasonal carbon sequestration potential defined as the ratio between the change in CO₂ flux and the added alkalinity carbon equivalent averaged over 2090-2099 (a, c), and the 2090-2099 time-integrated excess CO₂ flux (OAE minus control run) (b, d). The red contour line represents the region of alkalinity addition.



Results

Lines 394-411: 'The effects of OAE on carbonate seasonality are reflected in seasonal carbon sequestration potential. While both in SSP1-2.6 and SSP3-7.0, the seasonal potential grows over the winter months and decreases over the summer months, spatial differences are present: the European region is characterised by larger variability, 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: this is related to the scenario-dependent chemical efficiency of OAE whereby, per unit of added alkalinity, higher atmospheric CO₂ 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).

Other than being more variable in the European region than in the coastline region, values are much higher in the former than in the latter, which is explained by the fact that excess carbon uptake is not confined to the place of alkalinity addition. This aspect is highlighted in panels (b) and (d): while most additional air-sea CO₂ flux takes place near the coastal shelves, with little increase over the open ocean, this excess downward flux extends beyond the region of OAE deployment (Palmiéri & Yool, 2024). Furthermore, compared to SSP1-2.6, high emissions strengthen the ocean carbon sink for the same amount of added alkalinity and within the same spatial extent, due to a lower buffer factor in a high-CO₂ 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 485-498: 'With regard to the seasonal carbon sequestration potential, as CO₂ 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. These findings imply that 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 464-473: 'In agreement with previous studies (Wang et al., 2023, Nagwekar et al., 2024, Guo et al., 2025, Wang et al., 2025), 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. 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 phase 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 474-484: 'In agreement with Schwinger (2022), OAE in our simulations amplifies the CO₂ seasonal flux under both SSPs, prompting greatest carbon uptake during winter, as OAE is found to amplify the seasonal cycle when highest CO₂ drawdown occurs naturally. Importantly, our results show that increased summer alkalinity leads to the strongest decrease in ocean pCO₂, causing summer conditions to shift from net outgassing to net uptake as a result of rapid air-sea re-equilibration. This change effectively turns the European region and the coastline region into year-round CO₂ 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 CO₂ flux following alkalinity addition remains in phase with MLD seasonality, maintaining largest CO₂ uptake over winter, agrees with Nawgekar et al. (2024), who showed that seasonal shifts of the air-sea CO₂ 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 35-37: ‘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 58-62: ‘One mCDR method under investigation is ocean alkalinity enhancement (OAE), which aims to accelerate the ocean’s CO₂ 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 CO₂’

- 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 73-75: ‘Conversely, variations in DIC drive CO₂ loss in winter, when enhanced vertical mixing and organic matter respiration increase carbon content at the top layer, and CO₂ 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 78-90: ‘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 CO₂ uptake within the annual cycle, causing asymmetrical or phase shifts to the air-sea CO₂ flux, or altering seasonal extrema. The location of OAE deployment may be affected by the seasonal driver of the air-sea CO₂ flux as well as by physical properties, like bathymetry or

regional ocean circulation. Furthermore, adding alkalinity at the ocean's surface, already supersaturated with respect to calcite and aragonite (Hartmann et al., 2023), may surpass critical thresholds, 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's pCO₂ seasonal cycle is expected to increase due to rising atmospheric CO₂ 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 78-105: '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 CO₂ uptake within the annual cycle, causing asymmetrical or phase shifts to the air-sea CO₂ flux, or altering seasonal extrema. The location of OAE deployment may be affected by the seasonal driver of the air-sea CO₂ flux as well as by physical properties, like bathymetry or regional ocean circulation. Furthermore, adding alkalinity at the ocean's surface, already supersaturated with respect to calcite and aragonite (Hartmann et al., 2023), may surpass critical thresholds, 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's pCO₂ seasonal cycle is expected to increase due to rising atmospheric CO₂ 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. Similarly, 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. Additionally, 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 risk potential of negative impacts also increases. However, an analysis that explores the effects of continuous coastal OAE deployment on the seasonal carbonate system under different emission pathways has been missing. Thus, here we focus on seasonal carbon dynamics using output data from an earth system model (ESM) that simulated OAE along the European coastline under a low- and a high-emission Shared Socio-economic Pathway (SSP) (SSP1-2.6 and SSP3-7.0, respectively).'

Materials and Methods

- L. 122: “with a horizontal resolution of $1/2^\circ$ ” – 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 $1/2^\circ$ 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 148-150: ‘As the model runs with a horizontal resolution of $1/2^\circ$, 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 $1.4 \mu\text{mol C m}^{-2} \text{ y}^{-1}$ ” – 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 150-153: ‘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 ($\text{Ca}(\text{OH})_2$) is reached. From 2035, this amount, which equals 27 Tmol y^{-1} of alkalinity (or 44 mol $\text{m}^{-2} \text{ y}^{-1}$), is held constant until the end of the century (Fig. 1c).’

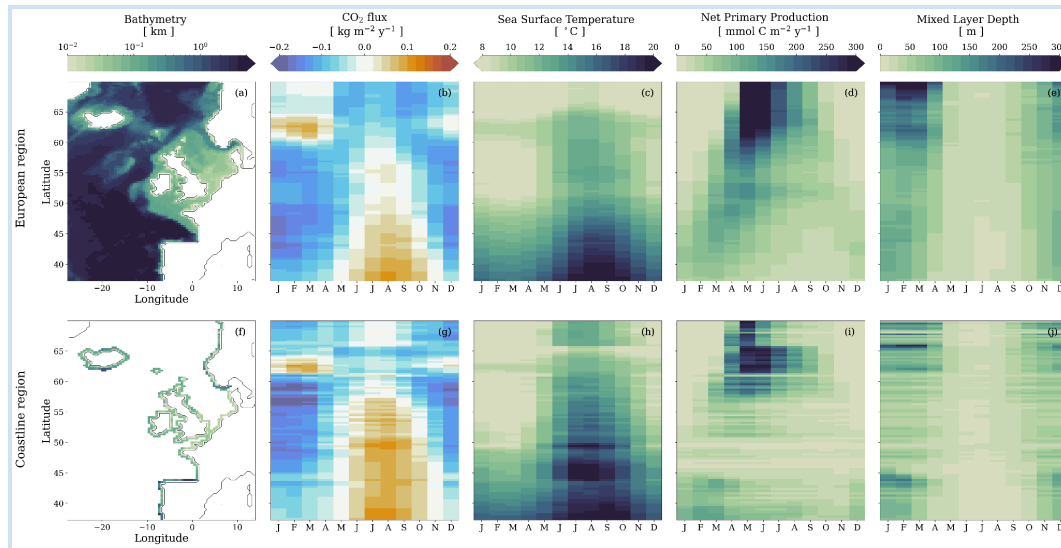
Results

- 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 215-247: ‘As a continental shelf pump, the European region plays an important role in carbon uptake dynamics 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 (Fig. 3a) and in the coastline region (Fig. 3f) for the CO_2 flux (Fig. 3b, g) and for some of its driving variables: SST (Fig. 3c, h), MLD-integrated NPP (Fig. 3d, i), and MLD (Fig. 3e, j).

Lines 225-229: ‘Figure 3: Hovmöller diagram of the zonally averaged European region (top) and coastline region (bottom) for bathymetry (a, f), the CO₂ 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 CO₂ flux plot, negative values indicate ocean uptake.’



For the air-sea CO₂ 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 (Fig. 3c, h), as the largest ocean CO₂ uptake happens in winter, when CO₂ solubility is strongest, while outgassing takes place in summer, when warm 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 sunlight and nutrient availability, while, from April to October, increasing productivity consumes CO₂ 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 (Fig. 3e) seems to neutralise CO₂ outgassing, while in the coastline region, where the MLD remains relatively shallower (Fig. 3j) and SST increases relatively more (Fig. 3e), the air-sea CO₂ flux is driven by chemical solubility and the largest CO₂ 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 CO₂ uptake (outgassing) in winter (summer).’

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

Lines 370-376: ‘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 pCO₂, which, due to fast air-sea exchange, turns net summer outgassing into a year-round carbon sink. OAE drives the largest excess CO₂ uptake in winter, as the seasonal air-sea CO₂ 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 CO₂ 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 (Fig. 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 atmosphere-ocean disequilibrium.’

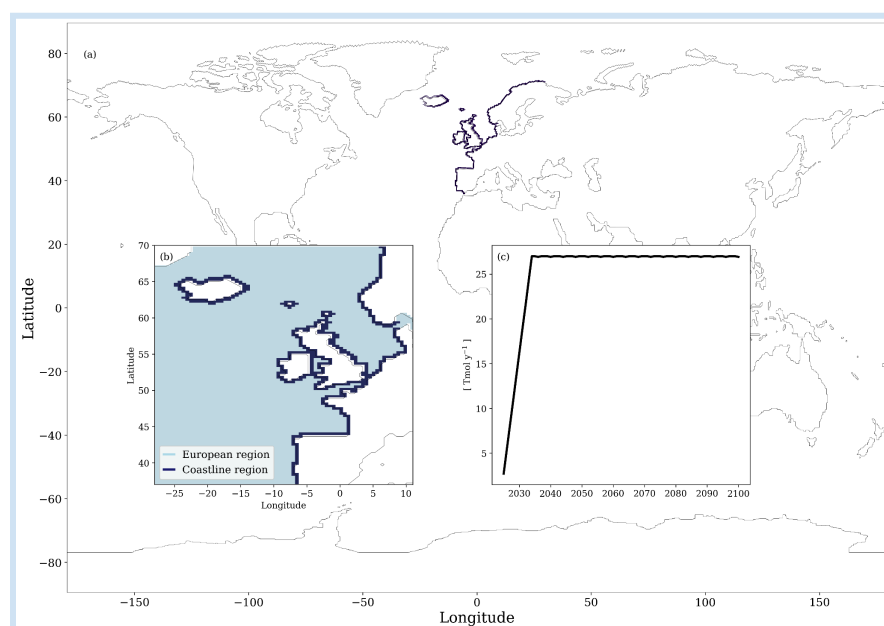
- L. 190: “the seasonal air-sea CO₂ flux in the study area”- unclear which “study area”; the North Sea or the red rectangle in Fig. 1?

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 141-145: ‘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 302-305: ‘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 $\mu\text{mol kg}^{-1}$. No clear amplitude change is visible in the remaining coastline region like off the coasts of Iceland, Spain and Norway’

- 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 305-307: ‘In SSP3-7.0 (Fig. 6c), the seasonal amplitude signal extends over a slightly wider area than in SSP1-2.6 (Fig. 6a), and the Norwegian and Icelandic coastlines show a slight increase of the alkalinity seasonal amplitude’

- 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 km^2) 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:

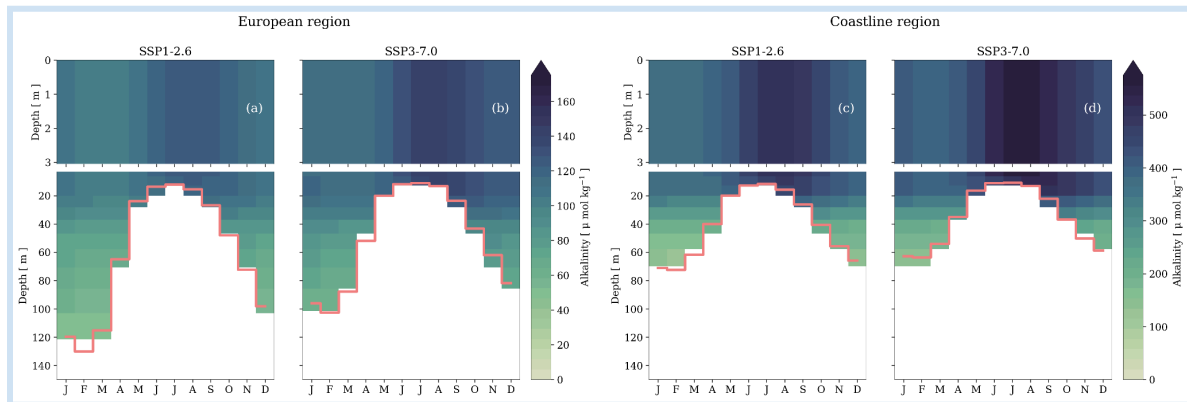
Lines 255-259: Table 1: Annual minimum and annual maximum values averaged over 2090-2099 for alkalinity, surface ocean pCO_2 , the air-sea CO_2 flux, and the mixed layer depth. Results are presented for the European region and the coastline region under both emission scenarios in the control and OAE runs. Note that air-sea CO_2 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 [$\mu\text{mol kg}^{-1}$]	(2198, 2210)	(2315, 2327)	(2167, 2184)	(2298, 2314)	(2184, 2203)	(2563, 2672)	(2138, 2162)	(2547, 2685)
Surface ocean pCO_2 [μatm]	(404, 433)	(357, 374)	(745, 807)	(674, 719)	(391, 452)	(188, 238)	(730, 836)	(344, 461)
Air-sea CO_2 flux [$\text{kg m}^{-2} \text{y}^{-1}$]	(-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:

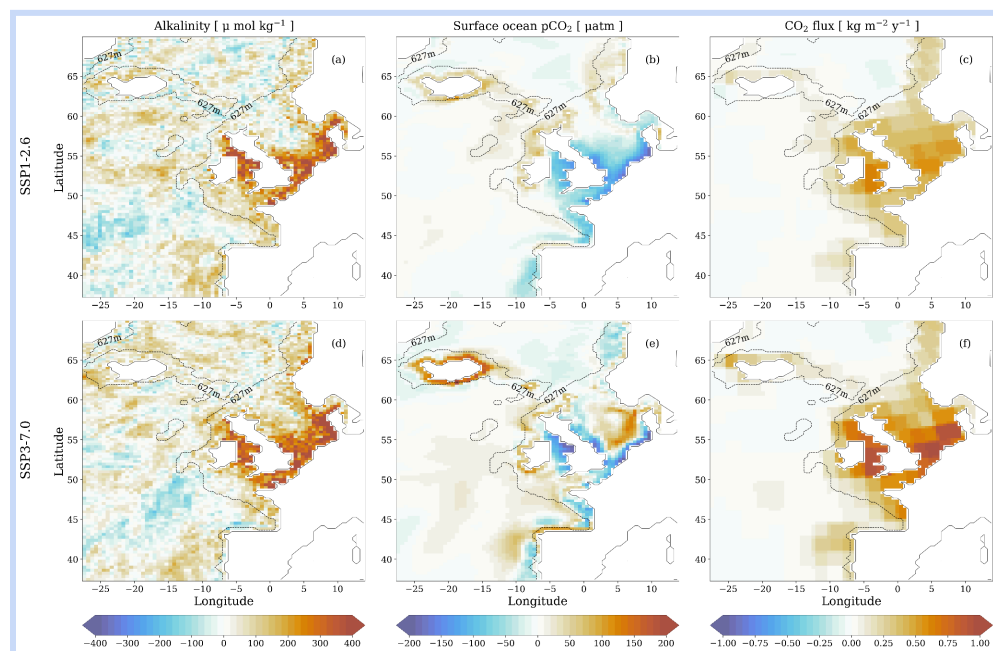
Lines 297-301: ‘Figure 5: Hovmöller diagram of the zonally averaged alkalinity change (OAE minus control run) as a function of depth over the first model layer (top) and over the mixed layer (bottom). The

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:

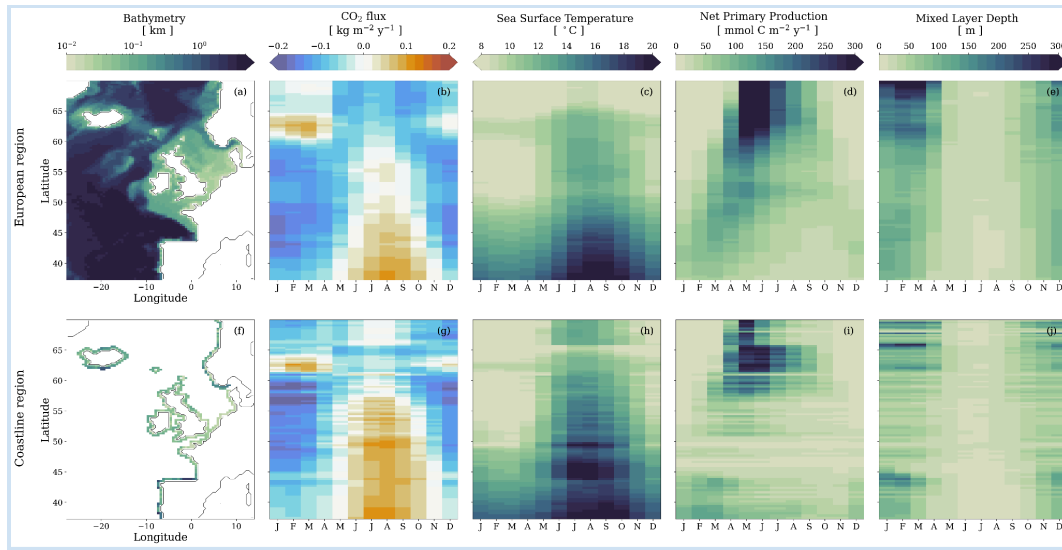
Lines 329-334: 'Seasonal amplitude change (OAE minus control run) averaged over 2090-2099 for MLD-averaged alkalinity (a, d), for surface ocean $p\text{CO}_2$ (b, e) and for the air-sea CO_2 flux (c, f). The top row shows SSP1-2.6 and the bottom row shows SSP3-7.0. CO_2 flux calculations are performed on the atmospheric component of FOCL, 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 225-229: ‘Figure 3: Hovmöller diagram of the zonally averaged European region (top) and coastline region (bottom) for bathymetry (a, f), the CO₂ 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 CO₂ 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 308-315: ‘Looking at surface ocean pCO₂, the European region (Fig. 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 (Fig. 3d), whereby carbon is consumed in photosynthetic fixation. In the OAE run, surface ocean pCO₂ 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 315-317: ‘While in the European region pCO₂ exhibits the same seasonality in both OAE and baseline simulations, in the coastline region, surface ocean pCO₂ 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 318-321: ‘In SSP1-2.6 (Fig. 4c), the seasonal amplitude of the ocean pCO₂ decreases from 61 μatm to 50 μatm, while in SSP3-7.0 (Fig. 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 206-209: ‘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 322-328: ‘OAE reduces surface ocean pCO₂ 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 behaviour indicates that, in our simulations, alkalinity addition produces the greatest pCO₂ decline during periods of naturally high CO₂ outgassing, resulting in a seasonal pCO₂ 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)

- 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 336-337: ‘In the SSP1-2.6 scenario (Fig. 6b), a distinct spatial pattern of pCO₂ 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 359-364: ‘In the European region, with OAE deployment the ocean’s CO₂ uptake potential is enhanced at all seasons: it ranges from 0.235 (0.327) kg CO₂ m⁻² yr⁻¹ in winter to 0.076 (0.053) kg CO₂ m⁻² yr⁻¹ in summer under SSP1-2.6 (SSP3-7.0). As OAE drives largest CO₂ drawdown during winter, it enhances the seasonal CO₂ flux, with a new amplitude of 0.168 kg CO₂ m⁻² yr⁻¹ in SSP1-2.6 and 0.292 kg CO₂ m⁻² yr⁻¹ in SSP3-7.0, compared to their respective controls (0.111 kg CO₂ m⁻² yr⁻¹ and 0.18 kg CO₂ 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 370-379: ‘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 pCO₂ which, due to fast air-sea exchange, turns net summer outgassing into a year-round carbon sink. OAE drives the largest excess CO₂ uptake in winter, as the seasonal air-sea CO₂ 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 CO₂ uptake than in the European region. 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 CO₂ 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 429-435: 'In the coastline region, this phase shift of surface alkalinity drives the reversal of ocean pCO₂ seasonality, though the CO₂ uptake, and the OAE-driven uptake increase, remains largest during winter, as CO₂ seasonality follows MLD seasonality. This leads to two main conclusions: on the one hand, increasing ocean disequilibrium with the overlying atmosphere turns summer 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 CO₂ dissolution in seawater 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 351-369: 'Regarding the CO₂ flux, seasonality is overall driven by temperature in our regional domain: the system outgasses (takes up) CO₂ in summer (winter), at lowest (highest) chemical solubility, and the largest CO₂ release happens between July and August. This pattern follows MLD seasonality, whereby summer warming shoals the mixed layer, reducing CO₂ uptake, and winter mixing deepens the mixed layer, enhancing the CO₂ flux. Under SSP1-2.6, the European region ranges from an uptake of 0.102 kg CO₂ m⁻² y⁻¹ between December and January and an outgassing of 0.009 kg CO₂ m⁻² y⁻¹ between July and August, while in SSP3-7.0, values are slightly more extreme: 0.142 kgCO₂ m⁻² y⁻¹ in winter and 0.038 kgCO₂ m⁻² y⁻¹ in summer

In the European region, with OAE deployment the ocean's CO₂ uptake potential is enhanced at all seasons: it ranges from 0.235 (0.327) kg CO₂ m⁻² yr⁻¹ in winter to 0.076 (0.053) kg CO₂ m⁻² yr⁻¹ in summer under SSP1-2.6 (SSP3-7.0). As OAE drives largest CO₂ drawdown during winter, it enhances the seasonal CO₂ flux, with a new amplitude of 0.168 kg CO₂ m⁻² yr⁻¹ in SSP1-2.6 and 0.292 kg CO₂ m⁻² yr⁻¹ in SSP3-7.0, compared to their respective controls (0.111 kg CO₂ m⁻² yr⁻¹ and 0.18 kg CO₂ m⁻² yr⁻¹). This results in a seasonal amplitude enhancement of 51% and of 62% in the low- and high-emission scenario, respectively. In the coastline region, the signal is larger than in the European region: the CO₂ flux seasonal amplitude is 0.329 kg CO₂ m⁻² yr⁻¹, therefore more than doubling the amplitude in the control run, which amounts to 0.114 kg CO₂ m⁻² yr⁻¹. With an amplitude of 0.505 kg CO₂ m⁻² yr⁻¹, the OAE seasonal CO₂ flux in SSP3-7.0 is more than 2.5 times larger than the control (0.199 kg CO₂ 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:

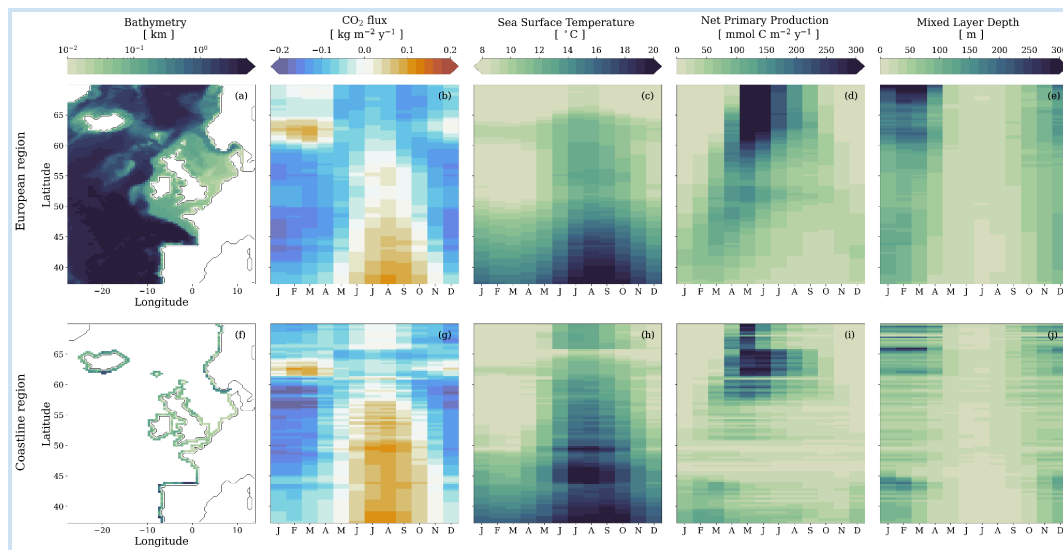
Lines 359-364: 'In the European region, with OAE deployment the ocean's CO₂ uptake potential is enhanced at all seasons: it ranges from 0.235 (0.327) kg CO₂ m⁻² yr⁻¹ in winter to 0.076 (0.053) kg CO₂ m⁻² yr⁻¹ in summer under SSP1-2.6 (SSP3-7.0). As OAE drives largest CO₂ drawdown during winter, it enhances the seasonal CO₂ flux, with a new amplitude of 0.168 kg CO₂ m⁻² yr⁻¹ in SSP1-2.6 and 0.292 kg

CO₂ m-2 yr-1 in SSP3-7.0, compared to their respective controls (0.111 kg CO₂ m-2 yr-1 and 0.18 kg CO₂ 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.

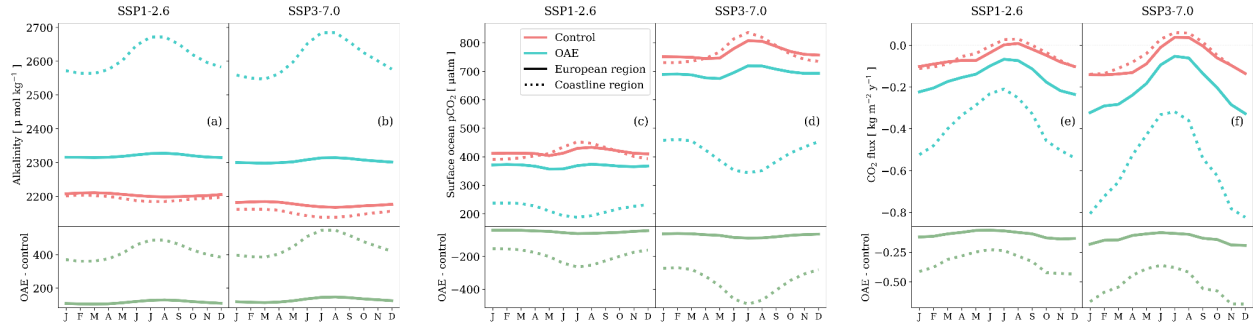
Lines 225-229: ‘Figure 3: Hovmöller diagram of the zonally averaged European region (top) and coastline region (bottom) for bathymetry (a, f), the CO₂ flux (b, g), sea surface temperature (c, h), MLD-integrated net primary production (d, i), and the mixed layer depth (e, j) over the 2090-2099 mean. In the CO₂ 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 270-276: ‘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 pCO₂ in SSP1-2.6 (c) and in SSP3-7.0 (d), and for the CO₂ flux in SSP1-2.6 (e) and in SSP3-7.0 (f), with the respective difference depicted by the green line. Continuous lines represent the European region and dashed lines represent the coastline region. In the CO₂ 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 206-209: ‘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 330-334: ‘Figure 6: Seasonal amplitude change (OAE minus control run) averaged over 2090-2099 for MLD-averaged alkalinity (a, d), for surface ocean pCO₂ (b, e) and for the air-sea CO₂ flux (c, f). The top row shows SSP1-2.6 and the bottom row shows SSP3-7.0. CO₂ flux calculations are performed on the atmospheric component of FOCL, 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 CO₂ uptake elsewhere. In Palmiéri & Yool (2024), for example, it was estimated that about 50% of CO₂ uptake favoured by global coastal OAE happened remotely from the alkalinity injection sites, as it is partially displayed in Fig. 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 474-476: ‘In agreement with Schwinger (2022), OAE in our simulations amplifies the CO₂ seasonal flux under both SSPs, prompting greatest carbon uptake during winter, as OAE is found to amplify the seasonal cycle when highest CO₂ 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 this compares to previous studies:

Lines 475-485: ‘In agreement with Schwinger (2022), OAE in our simulations amplifies the CO₂ seasonal flux under both SSPs, prompting greatest carbon uptake during winter, as OAE is found to amplify the seasonal cycle when highest CO₂ drawdown occurs naturally. Importantly, our results show that increased summer alkalinity leads to the strongest decrease in ocean pCO₂, causing summer conditions to shift from net outgassing to net uptake as a result of rapid air–sea re-equilibration. This change effectively turns the European region and the coastline region into year-round CO₂ 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 CO₂ flux following alkalinity addition remains in phase with MLD seasonality, maintaining largest CO₂ uptake over winter, agrees with Nawgekar et al. (2024), who showed that seasonal shifts of the air-sea CO₂ 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 $p\text{CO}_2$ 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 $p\text{CO}_2$ seasonality, though the CO_2 uptake, and the OAE-driven uptake increase, remains largest during winter, whereby colder months decrease SST, deepen the MLD and favour CO_2 dissolutions in seawater. This leads to two main conclusions: on the one hand, increasing ocean disequilibrium with the overlying atmosphere turns summer outgassing into net uptake year-round due to fast air-sea exchange; on the other hand, the CO_2 seasonal cycle keeps following MLD seasonality, independent of changes in alkalinity. In the coastline region, the MLD largely corresponds to the depth of the bathymetry for most of the year (Fig. 3), which implies that a shallow, well-mixed compartment may support surface alkalinity retention throughout the year, implying fast air-sea gas exchange. 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 atmosphere-ocean disequilibrium'

- 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 a low- and a high-emission scenario. 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 establish metrics on OAE detectability. At the same time, surface alkalinity in the coastal region increases by more than $500 \mu\text{mol kg}^{-1}$ 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.

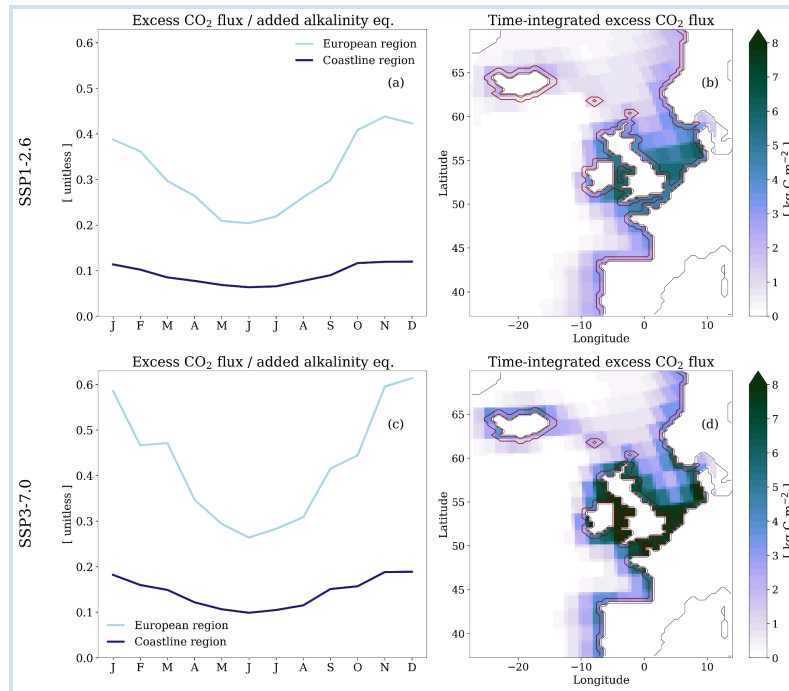
Many thank you for the suggestion. We fully agree that terminology needs to be used consistently throughout the text. We decided to not include a schematic in order to not overload the manuscript with figures but we adapted the manuscript to a less complicated and more consistent wording. We made some 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 370-379: ‘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 pCO₂ which, due to fast air-sea exchange, turns net summer outgassing into a year-round carbon sink. OAE drives the largest excess CO₂ uptake in winter, as the seasonal air-sea CO₂ 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 CO₂ uptake than in the European region. 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 CO₂ 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 389-393: ‘Figure 7: The seasonal carbon sequestration potential defined as the ratio between the change in CO₂ flux and the added alkalinity carbon equivalent averaged over 2090-2099 (a, c), and the 2090-2099 time-integrated excess CO₂ flux (OAE minus control run) (b, d). The red contour line represents the region of alkalinity addition.’



Lines 404-411: ‘Other than being more variable in the European region than in the coastline region, values are much higher in the former than in the latter, which is explained by the fact that excess carbon uptake is not confined to the place of alkalinity addition. This aspect is highlighted in panels (b) and (d): while most additional air-sea CO₂ flux takes place near the coastal shelves, with little increase over the open ocean, this excess downward flux extends beyond the region of OAE deployment (Palmiéri & Yool, 2024). Furthermore, compared to SSP1-2.6, high emissions strengthen the ocean carbon sink for the same amount of added alkalinity and within the same spatial extent, due to a lower buffer factor in a high-CO₂ 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 499-510: ‘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 (Fig. 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 CO₂ compared to a non-transient OAE simulation, due to elevated surface DIC concentrations and a decreasing ocean’s buffering capacity.

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 CO₂ 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 CO₂ 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 499-505: '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 (Fig. 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 CO₂ compared to a non-transient OAE simulation, due to elevated surface DIC concentrations and a decreasing ocean's buffering capacity.'

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 538-539: 'The present study addressed the changes to the seasonal carbon cycle driven by coastal OAE application under a low- and high-emission scenario.'

- 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 538-553: 'The present study addressed the changes to the seasonal carbon cycle driven by coastal OAE application under a low- and high-emission scenario. 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 $p\text{CO}_2$ more strongly in summer, when it is naturally highest, which, thanks to fast air-sea re-equilibration, turns summer net CO_2 outgassing into net uptake year-round. However, OAE drives the strongest CO_2 uptake enhancement in winter, when it is naturally strongest, as air-sea CO_2 flux remains in phase with the MLD seasonal cycle.

This study contributes to the understanding of OAE-driven CO_2 intra-annual variability in a continental shelf. 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 524-526: 'Furthermore, while freshwater input from rivers is modelled in FOCL, riverine alkalinity is not accounted for. As river runoff has a strong seasonal cycle, implementing such processes in the model would improve the accuracy of 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 547-553: 'This study contributes to the understanding of OAE-driven CO_2 intra-annual variability in a continental shelf. 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.'

REVIEWER 2:

Summary

The manuscript presents a coastal OAE study in which ALK is added to European coastal grid cells of a medium resolution model. The model is simulated for two emissions scenarios, and analysis focuses on the seasonal effects on the carbonate system. The main results include that OAE enhances uptake in the winter over the summer and that the North Sea represents a good region for future OAE deployment.

Assessment

Overall, I found the manuscript generally well-written but with a number of omissions that reduce its value to the literature. My major comments are as follows:

1. The manuscript focuses on a regional sea but **does not validate the performance of the model at this scale**. This is particularly important in the case of the coastline release areas, as the manuscript essentially takes the results from these areas at face value, despite potential issues around poor representation due to resolution, missing physical / biogeochemical processes or riverine inputs.
2. Presentation of the manuscript's results is slender with a **focus purely on the 2090s** with nothing about how the system then came into being, arguably absent spatial plots on changes in seasonality (e.g. maps of seasonal amplitudes), and confusing in-line use of important **metrics** that would be much more useful if **organised into a table**.
3. Although the work is performed globally, the analysis is strictly a regional affair, and it omits consideration of factors such as OAE performance (e.g. extra mol DIC per added eq ALK), where this happens, loss (to the region) of added ALK and extra DIC, and impacts on the model's natural ecosystem (NPP, CaCO₃ production, etc.). These affect the **assessment of requirements for MRV and the cost-benefit ratio**.
4. Main conclusions, such as the suitability of the North Sea for OAE, fail to note the dependence of this on the specific OAE approach here (i.e. addition of dissolved ALK), while the manuscript's caveats overlook model limitations in shelf seas areas, and potentially **oversell this region**.

My assessment is Major Revisions to address these gaps so that readers can both better understand this study and better assess its findings in the context of the wider OAE literature.

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:

- **Model validation of the region:** the point that was raised on regional model validation prompted us to include a new section that compares our model's data against GLODAPv2 datasets, using surface alkalinity, surface DIC, SST, and surface salinity (ocean pCO₂ observations were too sparse for this region). While the model is overall in agreement with the observations, we acknowledge that some biases exist and we include this aspect as a limitation in our manuscript, emphasising on important results that highlight its value.
- **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, a description of the background state of the two regions under investigation helps the reader understand changes in our OAE simulations.
- **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 built to summarise the main quantities described in the text 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 pCO₂ change and changes to the air-sea CO₂ 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 with a different setting from our implementation. The Discussion section now includes paragraphs of comparison between our study and previous research, which helps understand the new insights offered in our manuscript and its role in the wider OAE literature, highlighting that much of the results remain dependent on features like modes, rates, locations of alkalinity addition.

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

Specific comments

- Ln. 29-30: tweak to "... to lower its sea surface partial pressure" and "durable ocean storage" for clarity
Thank you for your comment. We changed the text to:

Lines 32-34: 'One potentially scalable method to remove CO₂ from the air is ocean alkalinity enhancement (OAE), which works to lower its sea surface partial pressure (pCO₂) and accelerate CO₂ sequestration and durable ocean storage.'

- Ln. 34-35: "OAE enhances CO₂ uptake in winter ... reduces ocean pCO₂ in summer" is potentially confusing as lowering pCO₂ in the summer might also be read as enhancing the conditions for CO₂ uptake

Thank you for pointing this out. After in-depth restructuring of the manuscript and analysis, here is a revised text of the key findings in the abstract:

Lines 34-40: 'This study explores how OAE might affect the seasonal carbon cycle, which plays a key role in the ocean's annual CO₂ 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 pCO₂ most strongly in summer, turning the region into a year-round carbon sink; b) the strongest air-sea CO₂ uptake enhancement 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'.

Additionally, this is how we reformulated the connection between lowest ocean pCO₂ and highest CO₂ uptake:

In the results:

Lines 370-379: '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 pCO₂ which, due to fast air-sea exchange, turns net summer outgassing into a year-round carbon sink. OAE drives the largest excess CO₂ uptake in winter, as the seasonal air-sea CO₂ 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 CO₂ uptake than in the European region. 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 CO₂ flux seasonal amplitude. As it will be described later, this behaviour is due to the lowering buffering capacity of the ocean under higher emissions.'

In the discussion:

Lines 427-435: 'Secondly, continuous OAE deployment induces surface ocean pCO₂ reduction at all seasons, but most strongly when the associated seasonal driver reduces the ocean CO₂ 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 pCO₂ seasonality, though the CO₂ uptake, and the

OAE-driven uptake increase, remains largest during winter, whereby colder months decrease SST, deepen the MLD and favour CO₂ dissolutions in seawater. This leads to two main conclusions: on the one hand, increasing ocean disequilibrium with the overlying atmosphere turns summer outgassing into net uptake year-round due to fast air-sea exchange; on the other hand, the CO₂ seasonal cycle keeps following MLD seasonality, independent of changes in alkalinity.'

- Ln. 36-37: grammar – switch “a region with a shallow bathymetry” to “regions with shallow bathymetry”; also, perhaps change “fast” to “faster” on Ln. 38

Thank you for the suggestion. This sentence has been removed due to changes in the analysis following some of your and other reviewers' comments. This will be argued more extensively in later responses.

- Ln. 130: correct the Chien et al. (2022) citation to the published paper and not the Discussions manuscript:

Chien, C.-T., Durgadoo, J. V., Ehlert, D., Frenger, I., Keller, D. P., Koeve, W., Kriest, I., Landolfi, A., Patara, L., Wahl, S., and Oschlies, A.: FOCI-MOPS v1 – integration of marine biogeochemistry within the Flexible Ocean and Climate Infrastructure version 1 (FOCI 1) Earth system model, *Geosci. Model Dev.*, 15, 5987–6024, <https://doi.org/10.5194/gmd-15-5987-2022>, 2022.

Thank you for pointing this out. We updated the reference:

Lines 590-593: 'Chien, C.-T., Durgadoo, J. V., Ehlert, D., Frenger, I., Keller, D. P., Koeve, W., Kriest, I., Landolfi, A., Patara, L., Wahl, S., and Oschlies, A.: FOCI-MOPS v1 – integration of marine biogeochemistry within the Flexible Ocean and Climate Infrastructure version 1 (FOCI 1) Earth system model, *Geosci. Model Dev.*, 15, 5987–6024, <https://doi.org/10.5194/gmd-15-5987-2022>, 2022.'

- Ln. 130: see my comment below too, but the validation here is at a global scale while your analysis is at the regional scale; so it does not especially help with ground-truthing your North Sea study

Many thanks for raising this point. We fully acknowledge that a regional validation of our model was missing. We added a dedicated section to address the validation against GLODAPv2 datasets for alkalinity, DIC, surface salinity and SST, and we also accept this as a limitation in a new Limitations section that describes the caveats of using FOCI-MOPS in this study. See answers to your specific comments below.

- Ln. 141: O'Neill et al. (2016) is the protocol for the ScenarioMIP simulations, not for general guidance on spin-up or Historical simulations; you should also add Eyring et al. (2016)

Thank you for the comment. We added the reference by Eyring et al. (2016):

Lines 135-136: 'All spin-ups, control simulations and forcings adhered to the CMIP6 protocol (O'Neill et al., 2016, Eyring et al., 2016).'

Lines 594-596: 'Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, *Geoscientific Model Development*, 9, 1937–1958, 2016.'

- Ln. 147: is the addition region really 50km or is it the width of a single grid coastal cell?; and if the latter, you may find that the width of the addition area changes with latitude because of grid distortion; I assume that, where the amounts of alkalinity added are quantified later that proper account is taken of varying grid cell areas

Thank you for pointing this out. Indeed, the alkalinity is applied to a single grid coastal cell which, as you suggested, implies grid distortion with latitude. We applied the grid cell area weighting to the analysis but we didn't make this clear enough in the text. We explained this process in depth in the text:

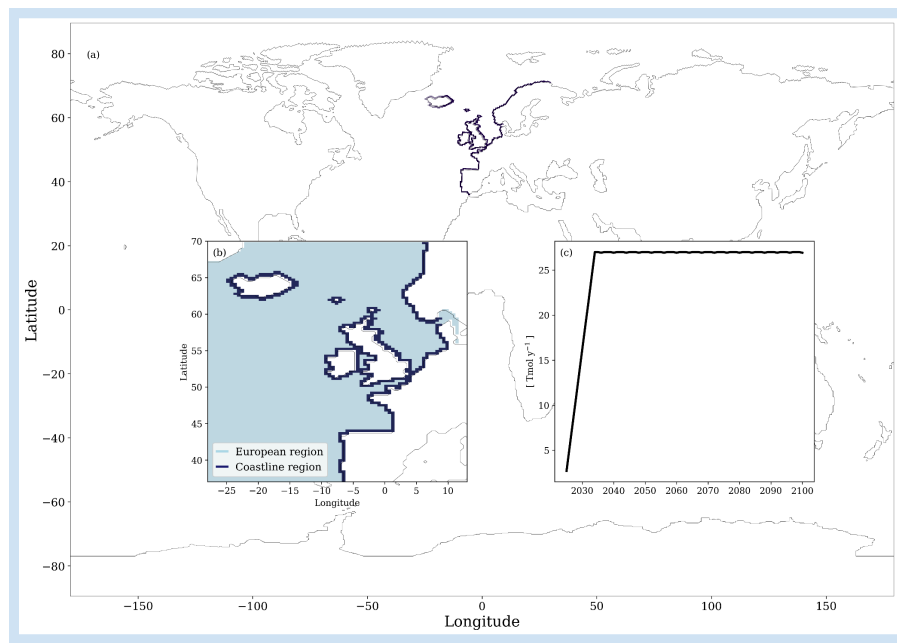
Lines 146-150: 'In the OAE runs, alkalinity is introduced continuously and evenly into the surface layer of the coastal grid cells outlined by the coloured line in Fig. 1a, spanning a vertical depth of roughly 3 meters. As the model runs with a horizontal resolution of $1/2^\circ$, this corresponds to approximately 55 km in the meridional direction and 45 km zonally in southern Europe, decreasing to about 30 km in northern Europe.'

You can find updated Figure 1 for reference in the answer below this one.

- Figure 1: Could this plot be improved to either show the full land mask (it's currently cut off on the east and west margins by unexplained curves) or by cropping the domain shown to remove these missing portions; more generally, you're showing a lot of domains that aren't part of your later analysis; you might also want to note in the caption that the x and y axes are not longitude and latitude – instead this plot seems to use the model's i-j grid

Thank you for the comments. We agree that Figure 1 could give a much clearer representation of the geographical extent of our analysis. Please, see below the updated figure with caption.

Lines 141-145: '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.'



- Figure 1: thank you for clearly including the British Isles as part of European waters – it helps us Remainers keep the flames of hope alive! ;-)

;-)

- Ln. 152-157: you don't say at what depth the alkalinity is added; and, while you make what you do clear, you might want to note how this compares to other studies – either here or in the discussion; it sounds a little like CDRMIP and different from the likes of Palmieri & Yool's 2024 study where ALK was added on the seafloor

Thank you for pointing this out. The new text reads:

Lines 146-148: 'In the OAE runs, alkalinity is introduced continuously and evenly into the surface layer of the coastal grid cells outlined by the coloured line in Fig. 1a, spanning a vertical depth of roughly 3 meters'.

Additionally, we touched upon how our method compares to other studies in the Discussion section:

Lines 450-463: 'In order to highlight the relevance of these findings, we place our results in the context of previous research that investigated OAE-induced seasonal changes under varying background emissions. Starting from the mode of OAE deployment, which has a strong impact on carbonate changes, most studies, including ours, have focused on surface alkalinity addition: at the coastline (Feng et al., 2017, Moustakis et al., 2025), throughout the global ocean (González and Ilyina, 2016, González et al., 2018), or at specific locations to explore regional dynamics (Ilyina et. al., 2013, Nagwekar et al., 2024). Similarly, our simulations explored the addition of a fast-reacting material, assuming rapid dissolution at the ocean surface. Importantly, Palmieri and Yool (2024) simulated the addition of about 29 Tmol y^{-1} alkalinity equivalent to the global shelves at the seafloor, finding that the depth of application has a minor impact on carbon sequestration potential. Furthermore, regarding the rate of alkalinity addition, we apply continuous OAE deployment, which implies a constant replenishment of surface alkalinity to drive air-sea disequilibrium. This approach differs from studies that investigated pulsed addition (He and Tyka, 2023, Zhou et al. 2024), which is likely to become a more realistic strategy in future deployment schemes.'

- Ln. 157: as you model alkalinity prognostically, you might want to express the quantity of alkalinity added in equivalents as well as carbon units

Thank you for the comment. We changed the text to:

Lines 150-153: '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 ($\text{Ca}(\text{OH})_2$) 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).'

- Ln. 165: the explanation for slicing to a European region feels a bit vague; you will need to be clear later on what the effect of cropping to this region is; in the context of the cited study, Palmieri & Yool (2024), you might be adding ALK in this region but the DIC is only absorbed outside this region

Thank you for raising this point. The slicing that we applied felt like a good compromise between keeping most of the region in the analysis and not diluting the seasonal signal too much. In addition, we were more interested in investigating dynamical changes in the proximity of the OAE location. Following your suggestion, we clearly stated how keeping the analysis confined to the defined area leaves out part of the carbon that may be taken up elsewhere. We made this especially clear by adding a figure on OAE efficiency within and outside the region of alkalinity addition. Please see the updated text below:

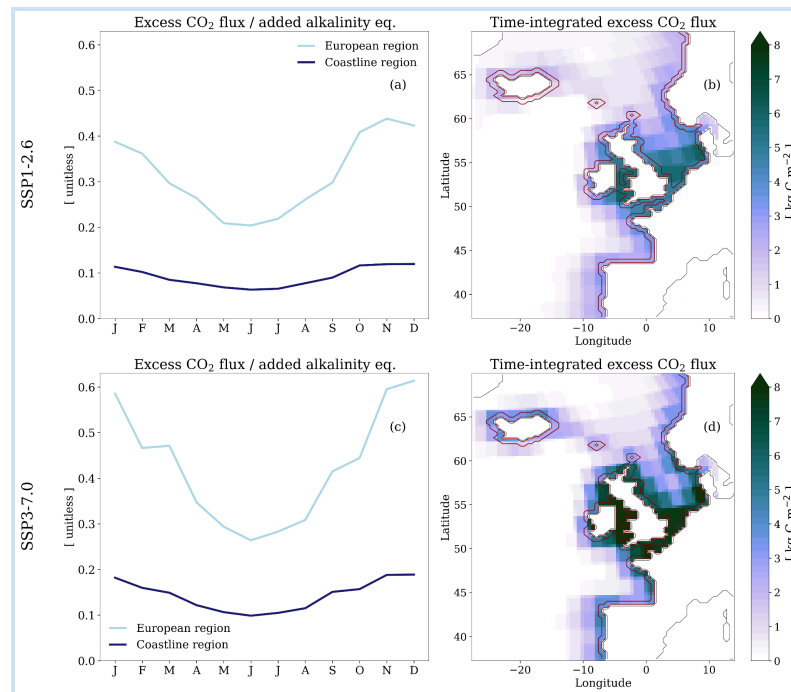
In the Methods section:

Lines 190-196: '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 Fig. 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 half 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.'

In the Results section:

Lines 389-393: 'Figure 7: The seasonal carbon sequestration potential defined as the ratio between the change in CO₂ flux and the added alkalinity carbon equivalent averaged over 2090-2099 (a, c), and the 2090-2099 time-integrated excess CO₂ flux (OAE minus control run) (b, d). The red contour line represents the region of alkalinity addition.'



Lines 404-411: 'Other than being more variable in the European region than in the coastline region, values are much higher in the former than in the latter, which is explained by the fact that excess carbon uptake is not confined to the place of alkalinity addition. This aspect is highlighted in panels (b) and (d): while most additional air-sea CO₂ flux takes place near the coastal shelves, with little increase over the open ocean, this excess downward flux extends beyond the region of OAE deployment (Palmiéri & Yool, 2024). Furthermore, compared to SSP1-2.6, high emissions strengthen the ocean carbon sink for the same amount of added alkalinity and within the same spatial extent, due to a lower buffer factor in a high-CO₂ world (Nagwekar et al., 2024).'

In the new Limitations section:

Lines 531-535: '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 CO₂ uptake elsewhere. In Palmiéri & Yool (2024), for example, it was estimated that about 50% of CO₂ uptake favoured by global coastal OAE happened remotely from the alkalinity injection sites, as it is partially displayed in Fig. 7.'

- Ln. 174: you say that “ocean pCO₂ and the CO₂ flux are written out only for the surface”, but they’re actually only CALCULATED for the surface too. They’re air-sea interface terms not 3D ocean terms. Thank you for your comment. Good point that CO₂ flux and CO₂ fugacity can be ‘written out’ only for the surface. We rephrased this sentence as follows:

Lines 199-200: ‘While ocean pCO₂ and the CO₂ flux are calculated only for the surface, alkalinity is represented over all 46 FOCI ocean layers.’

- Ln. 175: “alkalinity is calculated” isn’t quite right – it’s more *represented*

Thank you for the comment. We changed the phrasing of the sentence for alkalinity as well:

Lines 199-200: ‘While ocean pCO₂ and the CO₂ flux are calculated only for the surface, alkalinity is represented over all 46 FOCI ocean layers.’

- Ln. 182: some validation of the model seems in order; as already noted above, the Chien et al. (2022) paper deals with large scale validation and is not focused in the region here; and certainly not focused in the thin coastal strip that you use for parts of your analysis; given the importance of temperature SST seems a good start; ditto pCO₂ (if observational resolution permits it); I’m not sure how good DIC and ALK datasets are in this specific region, but if they’re available, definitely validate against these. Many thanks for raising the point about validation. We added a dedicated section to explore FOCI-MOPS fields against GLODAP fields for the region of alkalinity addition. While we were able to find data for ALK, DIC, salinity and SST, pCO₂ observations were either absent or too sparse in this region. Please see below the new section:

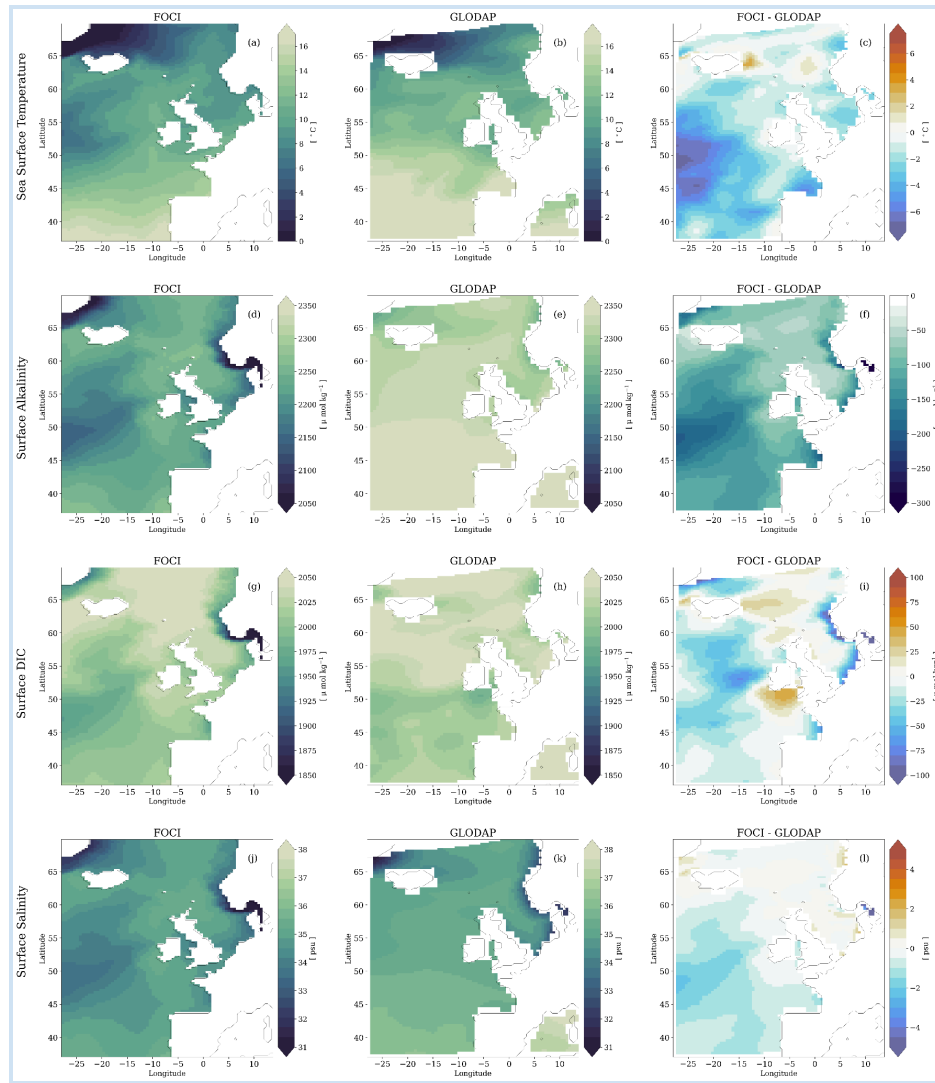
Lines 159-188:

‘2.3 Regional model validation

At the global scale, both alkalinity and DIC in FOCI-MOPS agree well with observations, while still showing a positive bias at the surface and a negative bias below 3000 meters of depth. However, model fidelity lowers towards the coasts, which are less resolved with a 1/2° resolution. While this is a common bias in global models that has been highlighted in Chien et al. (2022), here we validate FOCI-MOPS in the region where alkalinity is added using GLODAPv2 observations (Lauvset et al., 2016, Key et al., 2015) (Fig. 2).

For coastal sea surface temperature, FOCI-MOPS agrees well with GLODAPv2, with slightly lower values near the continental shelf. Towards the North Atlantic, FOCI-MOPS shows a prominent cold bias (Fig. 2c), which was already observed in previous model validation studies (Chien et al., 2022, Matthes et al., 2020). Such a feature is likely due to the lack of mesoscale dynamics, which affects the Gulf Stream path compared to an eddy-resolving ocean model (Matthes et al., 2020, Ojha et al., 2026, preprint).

Figure 2: Comparison of FOCI-MOPS mean fields (1972–2013) and 2021 GLODAP observations, along with their differences, for sea surface temperature (a, b, c), surface alkalinity (d, e, f), surface DIC (g, h, i), and surface salinity (j, k, l).



Generally, surface alkalinity has a minor negative bias compared to the GLODAPv2 dataset, which increases off the coasts of Norway and towards the open ocean (Fig. 2f). DIC fields in FOCI-MOPS agree well with observations, while showing a negative bias in the North Atlantic and a positive bias south of the Irish coasts. Importantly, by the Norwegian shelf and in the southern North Sea, the strong negative bias may have an impact on the background carbonate system under OAE application. A bias toward colder, lower-alkalinity conditions also reflects the fresh bias shown in Fig. 2l, which is stronger in the North Atlantic but absent towards the coast.

While FOCI-MOPS shows good agreement with GLODAPv2 observations, we recognise that the use of a lower-resolution model may limit the accuracy of absolute values in our simulations. However, we emphasise that our analysis focuses on differences between simulations (i.e. between an OAE run and a control run, or between SSPs), such that systematic errors are expected to affect experiments similarly and therefore largely cancel.

Additionally, we added this as a limitation to the new Limitations sections:

Lines 516-526: ‘Some limitations and future recommendations can be drawn from this study. With regard to FOCI-MOPS, the ESM represents coastal biogeochemical processes less well compared to the open

ocean (Chien et al., 2022), which may affect the accuracy of absolute values in the region of alkalinity addition. While model results are mostly in agreement with GLODAPv2 observations, some of the biases may affect the veridicity of output values. Alkalinity in the Baltic Sea, for example, is poorly resolved by FOCI, which could have an impact on the North Sea boundary conditions. However, since our analysis focuses on relative differences between runs, the main conclusions in this manuscript would be less affected by such structural biases, as these are expected to affect both simulations similarly. Furthermore, while freshwater input from rivers is modelled in FOCI, riverine alkalinity is not accounted for. As river runoff has a strong seasonal cycle, implementing such processes in the model would improve the accuracy of OAE simulations.'

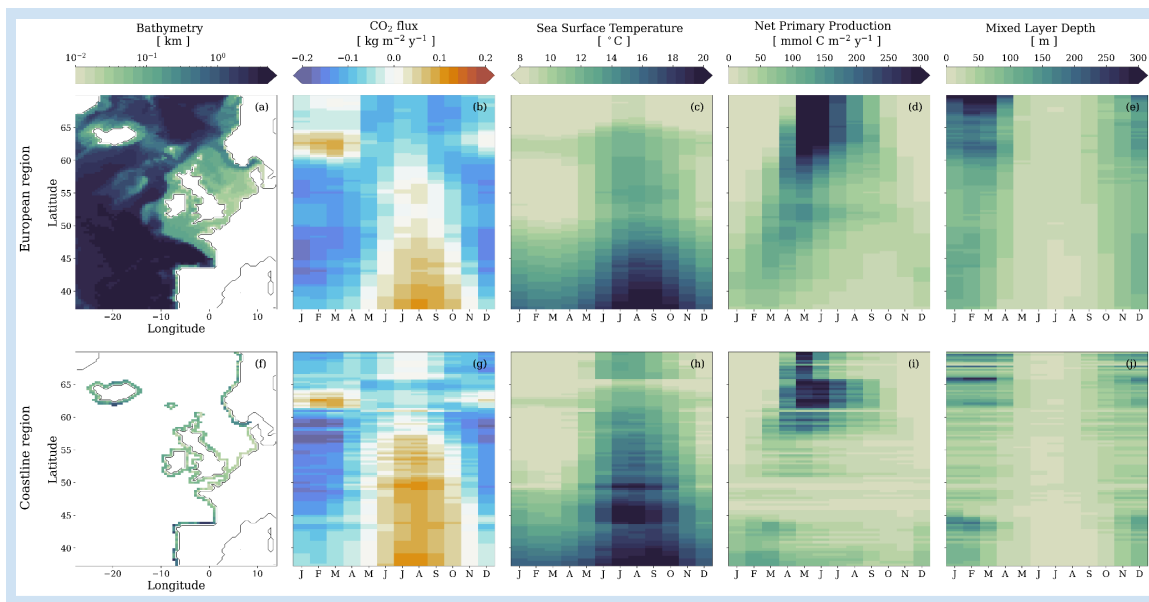
- Ln. 201: you note a North Sea section here – any chance it could be plotted on Figure 1?

Thank you for the comment. As already mentioned above, we realised that the North Sea section does not fit well within the scope of the analysis and we decided to replace it with a section on the seasonality of baseline variables for the two manuscript's domains, namely the European region and the coastline of addition (now highlighted in the updated Figure 1). Hence, we wouldn't need to add the North Sea transect in Figure 1.

- Figure 2: consider using a diverging palette (e.g. classic blue-white-red; or the one used in Figure 4) for the CO₂ flux so that zero flux is easier to spot

Thank you for the suggestion. The palette of the air-sea CO₂ flux plot has been changed to a diverging palette. Please, see the updated Figure and its associated caption. The order of the plots has also been changed, following your input in a later comment.

Lines 225-229: 'Figure 3: Hovmöller diagram of the zonally averaged European region (top) and coastline region (bottom) for bathymetry (a, f), the CO₂ 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 CO₂ flux plot, negative values indicate ocean uptake.'



- Figure 2: I like that you kept the graininess of the model grid here – much more honest than the interpolated contour plots people use

Thank you :-)

- Figure 2: why show surface NPP when, due to mixing, it's surface layer productivity that controls CO₂ uptake?

Thank you for your comment. We were slightly confused by what would be best to plot here. Did you mean that it could be more consistent to plot MLD-integrated NPP? If yes, we added the MLD-integrated NPP as highlighted in figure 3 above this comment.

- Figure 2: the ordering of the subplots seems a little arbitrary; by default, I would have gone SST, MLD, NPP, CO₂ flux to reflect some sort of process-ordering, but in reading your results, I might have at least put SST and CO₂ flux closer together so it's easier to see the common patterns.

Thank you for this comment. We initially intended to show all the drivers and then the outcome (CO₂ flux) but we see how your suggestion makes the figure more readable. We put SST close to air-sea CO₂ flux to show how temperature has a predominant effect driving air-sea CO₂ flux, especially at low latitudes, while NPP comes right before SST to show how that has a much higher impact in driving the flux direction at higher latitudes. To avoid copy-pasting the figure twice, we refer you to the comments just above this one.

- Ln. 217: a general comment I'd make about this section is that there are lots of numbers given in the text and it would be better to consolidate these into a table so that readers can clearly see the major features identified both geographically and between scenario runs.

Many thanks for suggesting this. We built a simple table that summarises average values for the time-period that we focus on. See the caption and the table below.

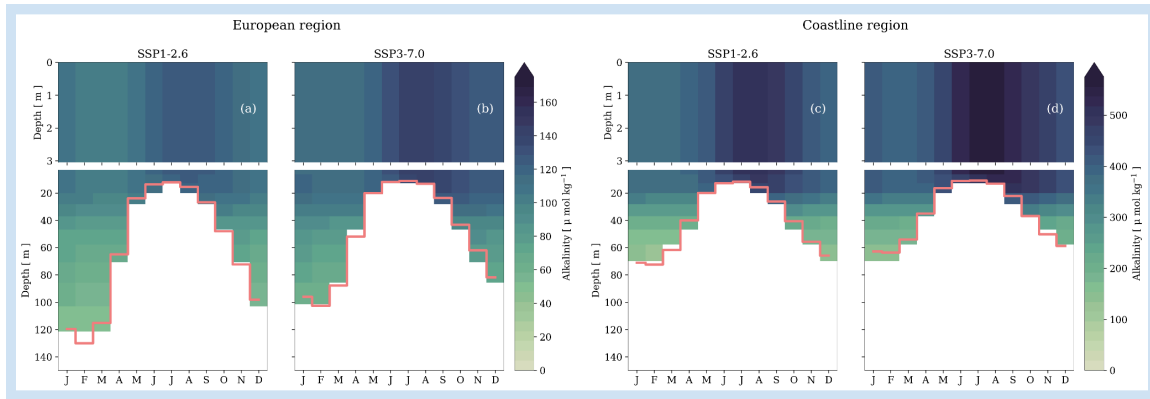
Lines 255-259: 'Table 1: Annual minimum and annual maximum values averaged over 2090-2099 for alkalinity, surface ocean pCO₂, the air-sea CO₂ flux, and the mixed layer depth. Results are presented for the European region and the coastline region under both emission scenarios in the control and OAE runs. 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 pCO ₂ [μatm]	(404, 433)	(357, 374)	(745, 807)	(674, 719)	(391, 452)	(188, 238)	(730, 836)	(344, 461)
Air-sea CO ₂ 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)

-Ln. 227: vertical processes are invoked here but no results are presented in support of these; perhaps a comparison of Hovmöllers of decadal-averaged ALK from the two scenarios (or differences of scenarios from their control twins) would assist?

Thank you for the comment. We fully agreed that a plot showing vertical profiles was missing in support of the description in the text. We added a hovmöller of the change in monthly averages for the last simulation decade (for consistency with the other plots). See below the new figure and its caption:

Lines 297-301: ‘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.’



Lines 284-295: ‘Importantly, under both emission scenarios and in both the European and the coastline regions, alkalinity addition reverses its surface seasonal cycle, with summer values exceeding winter values. This reversed pattern is highlighted in Fig. 5, where seasonal alkalinity is shown as a function of depth: while under natural conditions, alkalinity increases with depth and winter mixing helps replenish the upper ocean from deeper layers, thus following MLD seasonality, in the OAE simulations, alkalinity is added at the surface in our simulations, and stronger vertical stratification in summer leads to greater alkalinity retention.’

In all OAE runs, while alkalinity mostly accumulates in the first ocean layer (top row), the rest of the mixed layer (bottom row) also reflects an alkalinity increase, which is higher in summer than in winter, leading to the seasonal shift that is observed in Fig. 4a, b. Surface alkalinity accumulation is higher in the coastline region, compared to the European region, due to a much higher alkalinity input in the region of addition, and in SSP3-7.0, compared to SSP1-2.6.’

- Figure 3: is the “coastline average” the values in the grid cells indicated in Figure 1?

Thank you for pointing this out. The coastline average indeed is the average along the coastal grid cells. We see how we did not make the description of the region selection fully clear and we changed the text as follows:

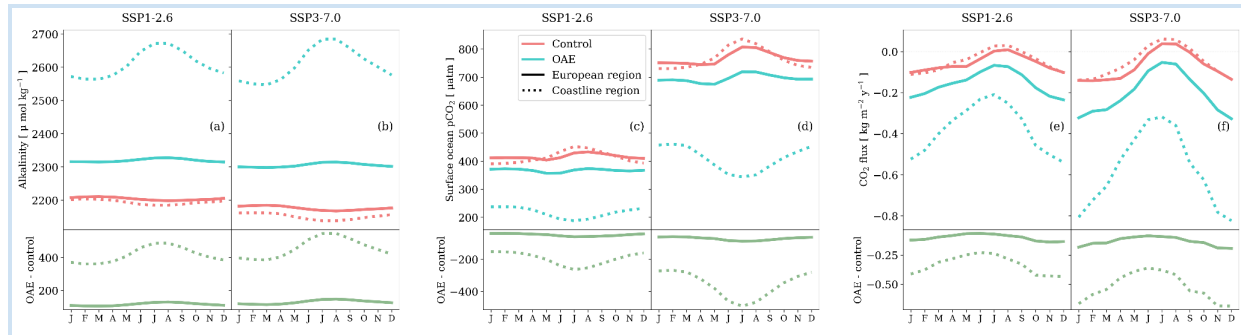
Lines 190-194: ‘Our analysis focuses on the comparison between two regions: the ‘coastline region’, which corresponds to the shelf grid cells highlighted by the dark blue line in Fig. 1b, offers details on regime shifts that take place at the epicenter of the domain; the ‘European region’, which corresponds to the coloured ocean region in Fig. 1b, measures how the European system as a whole might respond to OAE.’

Additionally, we changed all references and figure labels to ‘European region’ and ‘coastline region’ to avoid confusion and be consistent throughout the manuscript and figures.

- Figure 3: might it be an idea to have the upper and lower plots sharing the same vertical axes so it’s easy to compare them?; it looks like it should generally work

Thank you for suggesting this. Based on your comment, we decided to combine the upper and lower plot to allow for easier comparison. See below the updated caption of Figure 3 (now figure 4).

Lines 270-276: ‘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 pCO₂ in SSP1-2.6 (c) and in SSP3-7.0 (d), and for the CO₂ flux in SSP1-2.6 (e) and in SSP3-7.0 (f), with the respective difference depicted by the green line. Continuous lines represent the European region and dashed lines represent the coastline region. In the CO₂ flux plots, negative values indicate ocean uptake.’



- Figure 3: looking at this figure’s results from the 2090s makes me wonder if there’s any value in exploring the same (or similar) quantities across the whole of the simulation period?; perhaps amplitude of seasonality would be good to see given the two scenarios clearly diverge on properties like this

Thank you for raising this suggestion. While we think that plotting the whole simulation period would bring clarity on how the system developed from its initial state, we argue that such an analysis would slightly diverge from the scope of this manuscript, which specifically focuses on the seasonal changes driven by OAE and is less focused on understanding the evolution from initial conditions. Additionally, a paper is being drafted at the moment based on the same simulations which will look further into such dynamics from the beginning of the simulations.

- Figure 4: one can imagine that the calculation of CO₂ flux on a much coarser grid that’s implied here might affect the results; it might be helpful to articulate how exactly the CO₂ flux calculation is done – i.e. are ocean properties (SST, DIC) averaged to the atmospheric grid and then pCO₂, CO₂ flux is calculated, or is ocean pCO₂ calculated on the ocean grid averaged to the atmospheric grid and then CO₂ flux calculated, or is everything done on the ocean grid, and the CO₂ flux is integrated to the lower-resolution atmospheric grid?; most models I know do the latter; in any case, and explanation – probably in the methods – is needed to explain what’s done and what the implications of this are

Thank you for this comment. We agree that the grid on which the air–sea CO₂ flux is calculated is particularly relevant for a regional analysis of European coastal waters, where strong gradients in SST, sea ice, winds, biological activity, alkalinity, and surface ocean pCO₂ can occur over relatively short distances.

The calculation of the CO₂ flux follows the existing FOCI coupling architecture, where surface fluxes are calculated in the atmospheric component. A practical advantage of this approach is that the CO₂ flux is computed consistently with the rapidly varying atmospheric boundary-layer state, including wind speed and atmospheric CO₂, which directly control air–sea gas exchange. However, for the regional coastal analysis presented here, this also implies that oceanic surface CO₂ information is first remapped to the coarser atmospheric grid before the flux is calculated, leading to smoothing of sub-atmospheric-grid coastal gradients. We have now added this description to the Methods section and we also discussed the implication of this coupling strategy.

Lines 124-131: ‘In FOCI-MOPS, the ocean biogeochemical state, including DIC and alkalinity, is calculated on the NEMO-MOPS ocean grid, while the coupled air–sea CO₂ flux information is transferred through

OASIS3-MCT from the ORCA05 ocean grid to the coarser atmospheric T63 grid. The CO₂ flux is then calculated in the atmospheric component of FOCI and subsequently remapped conservatively back to the ocean grid, where it is applied as the surface DIC boundary flux (Matthes et al., 2020). Since the CO₂ flux calculation is performed on the less resolved atmospheric grid, sub-atmospheric-grid oceanic gradients are smoothed before the flux is calculated.'

- Figure 4: is it informative to plot the point-by-point correlation between delta-ALK and delta-pCO₂?; this might help clarify the text around different regions responding differently; and use of different coloured points for the two scenarios could allow them to be plotted on the same axes, and this might pull-out the divergence in the two runs seen in the region of the North Sea east of Scotland and west of Denmark

Thank you for this suggestion. We tried to plot what you suggested (by latitudinal bands) but the result was not informative to conclude any consistent pattern due to the amount of data points. In addition, we concluded that higher / lower amplitude may be induced by how strong the summer pCO₂ reduction is (i.e. if the summer reduction of ocean pCO₂ is strong enough, the seasonal cycle is amplified as well as reversed). We explain this in the text below:

Lines 344-350: 'Such a strong latitudinal and scenario divergence in the seasonal amplitude of surface ocean pCO₂ may be due to different factors: north of 60° N, where the air-sea CO₂ flux is driven by its biological component (Fig. 3d), the seasonal cycle could respond differently from the European region and the coastline region averages, where the CO₂ flux is controlled by SST; at lower latitudes in SSP3-7.0, the increasing seasonal cycle of surface ocean pCO₂, which is spatially confined to the coastal shelves, is probably driven by an even stronger OAE-induced pCO₂ decline over summer, which increases its seasonal amplitude as it is highlighted in Fig. 3d for the coastline region.'

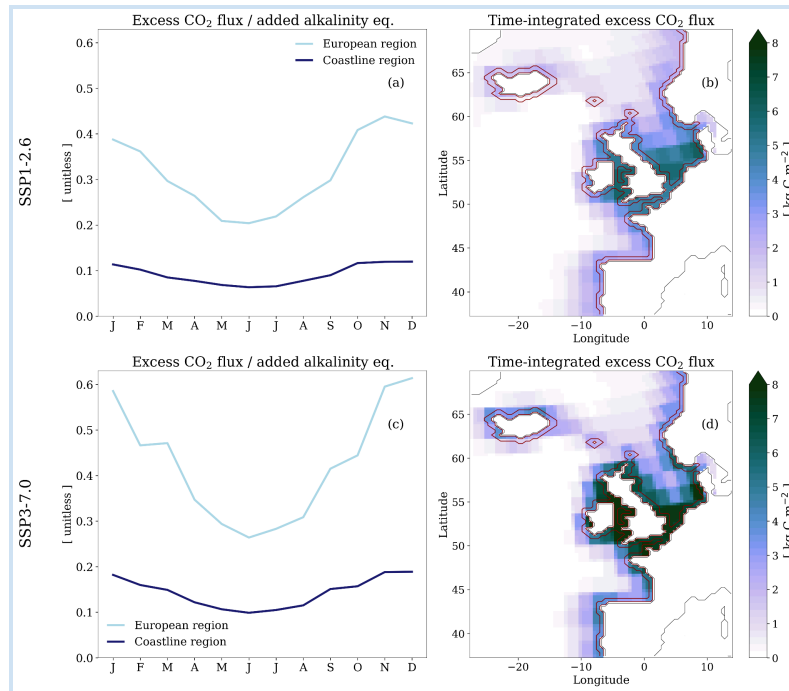
- Ln. 293-303: per my earlier remarks, consolidating the figures here in a table that perhaps separated the numbers between regions as well as between the scenarios might help the manuscript articulate the important differences better; text descriptions are less clear than even a simple table

Thank you for remarking this. We fully agree that summarising the main values in a table would add clarity to the text. We addressed this issue in an earlier response, where the new table is shown. We refer you to the comment above.

- Ln. 339: "becomes more sensitive" – I'm unclear on what becoming more sensitive means for carbonate chemistry; perhaps illustrating with a clear example ("for instance, ...") would help

Thank you for your input. We realise that the term 'sensitive' is potentially misleading and we removed references within the text. Please, read the updated paragraphs that refer to this mechanism below, drawing from new Figure 7:

Lines 389-393: 'Figure 7: The seasonal carbon sequestration potential defined as the ratio between the change in CO₂ flux and the added alkalinity carbon equivalent averaged over 2090-2099 (a, c), and the 2090-2099 time-integrated excess CO₂ flux (OAE minus control run) (b, d). The red contour line represents the region of alkalinity addition.'



Lines 394-403: ‘OAE-driven impacts on carbonate seasonality are reflected on the seasonal carbon sequestration potential. While both in SSP1-2.6 and SSP3-7.0, the seasonal potential grows over the winter months and decreases over the summer months, spatial differences are present: the European region is characterised by larger variability, 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: this is related to the scenario-dependent chemical efficiency of OAE whereby, per unit of added alkalinity, higher atmospheric CO₂ 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).’

Lines 502-510: ‘This finding agrees with Schwinger et al. (2024), who showed that increasing emissions drive an even further ocean uptake of anthropogenic CO₂ compared to a non-transient OAE simulation, due to elevated surface DIC concentrations and a decreasing ocean’s buffering capacity. 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 CO₂ 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 CO₂ and, most importantly, due to a decreasing buffer factor.’

- Ln. 352: “stronger chemical leverage” – again, I’m not sure what exactly is meant by this

Thank you for raising this point. After substantial restructuring following your comment, this is the new texts that address the point mentioned above:

Lines 399-403: ‘Additionally, high emissions drive a larger carbon uptake potential: this is related to the scenario-dependent chemical efficiency of OAE whereby, per unit of added alkalinity, higher atmospheric CO₂ 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).’

Lines 507-510: ‘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 CO₂ and, most importantly, due to a decreasing buffer factor’.

- Ln. 353: “exacerbated by OAE implementation” makes it sound like the specifics of how OAE is implemented are important when you might just mean the use of OAE in general

Thank you for the comment. As you suggested, the intention was to state that OAE in general exacerbates the outcome that we see. However, due to substantial changes in the text, this sentence was removed.

- Ln. 352-353: this concluding sentence is similarly difficult to follow without a concrete example that would help readers follow; do, for instance, you mean that

Thank you for pointing this out. We fully agreed that the connection between higher emissions and higher carbon sequestration was poorly described. We removed this sentence and added more information on the interpretation of the results as per your previous comments. We refer you to previous responses on high versus low emissions, where we describe the interpretation of the results.

Lines 503-511: ‘This finding agrees with Schwinger et al. (2024), who showed that increasing emissions drive an even further ocean uptake of anthropogenic CO₂ 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 CO₂ 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 CO₂ and, most importantly, due to a decreasing buffer factor.’

- Ln. 360-361: same point I made about the abstract; i.e. this sentence, which reads like it’s making a nice compare-and-contrast statement, is kind-of talking about apples and oranges by flipping between CO₂ flux for the winter but pCO₂ for the summer; looking at Figure 3, net flux is lowest in the summer when air-sea delta pCO₂ is actually the greatest; which points to perhaps other factors (winds and gas transfer velocity, mixing depth) as being important (but less acknowledged here)

Thank you for raising this inconsistency. We fully agree that the relationship between ocean pCO₂ and CO₂ flux changes were not addressed clearly enough in the text. Here’s an updated paragraph of the system dynamic:

Lines 370-379: ‘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 pCO₂ which, due to fast air-sea exchange, turns net summer outgassing into a year-round carbon sink. OAE drives the largest excess CO₂ uptake in winter, as the seasonal air-sea CO₂ 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 CO₂ uptake than in the European region. 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 CO₂ flux seasonal amplitude. As it will be described later, this behaviour is due to the lowering buffering capacity of the ocean under higher emissions.’

- Ln. 362: “sensitivity” – would this perhaps be better as “size of the response” or similar?; it’s not clear to me that readers will understand what “sensitivity” means here

Thank you for the comment. As per your previous comments, we agree that 'sensitivity' has a specific meaning and that 'the size of the response' would fit better in this context. See below the new paragraph where this sentence has been rephrased:

Lines 499-510: 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 (Fig. 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 CO₂ compared to a non-transient OAE simulation, due to elevated surface DIC concentrations and a decreasing ocean's buffering capacity. 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 CO₂ 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 CO₂ and, most importantly, due to a decreasing buffer factor.'

- Ln. 368: given the work focuses on a regional experiment in a major shelf sea, this list of limitations omits reference to the model's resolution and representation of both shelf seas physics and biogeochemistry; there's a mention of riverine inputs of ALK, which is good, but I thought MOPS was more an open ocean model than a shallow shelf seas model (I say this because the model I use is somewhat similar)

Thank you for raising this issue. In addition to the added section on model validation, we fully agreed that we should accept this as a limitation in our study and we added a new sentence to the Limitations section:

Lines 516-526: 'Some limitations and future recommendations can be drawn from this study. With regard to FOCI-MOPS, the ESM represents coastal biogeochemical processes less well compared to the open ocean (Chien et al., 2022), which may affect the accuracy of absolute values in the region of alkalinity addition. While model results are mostly in agreement with GLODAPv2 observations, some of the biases may affect the veridicity of output values. Alkalinity in the Baltic Sea, for example, is poorly resolved by FOCI, which could have an impact on the North Sea boundary conditions. However, since our analysis focuses on relative differences between runs, the main conclusions in this manuscript would be less affected by such structural biases, as these are expected to affect both simulations similarly. Furthermore, while freshwater input from rivers is modelled in FOCI, riverine alkalinity is not accounted for. As river runoff has a strong seasonal cycle, implementing such processes in the model would improve the accuracy of OAE simulations'.

- Ln. 364: the statement about locations like the southern North Sea may be dependent upon the mode of ALK addition used for OAE; where dissolution of particulate minerals is used to add the ALK, temperature effects may favour warmer equatorial waters; this is specifically examined in Palmieri & Yool (2024) where the effectiveness of different shelf seas at the global scale is evaluated

Thank you for raising this point. We should have clarified the fact that results may be dependent on the type of OAE deployment. In addition, as we dropped the North Sea section, we think that it would be more consistent to simply consider regions with shallow bathymetry and shallow MLD to be suitable for coastal OAE as alkalinity would accumulate more easily at the ocean surface. This is how we modified the text:

In the Introduction section:

Lines 78-90: '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 CO₂ uptake within the annual cycle, causing asymmetrical or phase shifts to the air-sea CO₂ flux, or altering seasonal extrema. The location of OAE deployment may be affected by the seasonal driver of the air-sea CO₂ flux as well as by physical properties, like bathymetry or regional ocean circulation. Furthermore, adding alkalinity at the ocean's surface, already supersaturated with respect to calcite and aragonite (Hartmann et al., 2023), may surpass critical thresholds, 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's pCO₂ seasonal cycle is expected to increase due to rising atmospheric CO₂ concentrations (Gallego et al., 2018), studying the influence of background emissions would help understand the role of different climate mitigation pathways on OAE deployment.'

In the Results section:

Lines 435-440: 'In the coastline region, the MLD largely corresponds to the depth of the bathymetry for most of the year (Fig. 3), which implies that a shallow, well-mixed compartment may support surface alkalinity retention throughout the year, implying fast air-sea gas exchange. 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 atmosphere-ocean disequilibrium'.

- Ln. 368: a style point, but I'd be inclined to move this whole paragraph into the Discussion rather than Conclusions; keep the Conclusions to your main findings (and maybe bullet-point them – but that really is a style point)

Thank you for the suggestion. We moved the Limitations paragraph to a new dedicated section below the Discussion. We decided to keep the Conclusions section more discursive, also following another reviewer's comment.

Lines 538-553: 'The present study addressed the changes to the seasonal carbon cycle driven by coastal OAE application under a low- and high-emission scenario. 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 pCO₂ more strongly in summer, when it is naturally highest, which, thanks to fast air-sea re-equilibration, turns summer net CO₂ outgassing into net uptake year-round. However, OAE drives the strongest CO₂ uptake enhancement in winter, when it is naturally strongest, as air-sea CO₂ flux remains in phase with the MLD seasonal cycle.

This study contributes to the understanding of OAE-driven CO₂ intra-annual variability in a continental shelf. 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.

- Ln. 384: on the subject of style points, maybe trim people to initials only in this paragraph

Thank you. We applied the changes you suggested, and the Author contribution section now reads:

Lines 556-559: 'Conceptualisation: C. C., D. P. K.; Performing model simulations: T. P. K.; Data curation: C. C., D. P. K.; Formal analysis: C. C.; Investigation: C. C.; Methodology: D. P. K., T. P. K.; Supervision: D.

P. K.; Validation: D. P. K.; Visualisation: C. C.; Writing – original draft: C. C. ; Writing – review & editing: C. C., D. P. K., N. M., T. P. K., S. A.’