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Impacts of Simulated Coastal Ocean Alkalinity Enhancement on the Seasonal Cycle of the Air-Sea CO_2 Flux and Surface Ocean pCO_2 in European Waters under a Low- and a High-Emission Scenario

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Key Points:

- Ocean Alkalinity Enhancement (OAE) aims to increase the ocean's potential to sequester and store atmospheric CO_2
- In our study area, OAE effects are strongest in enhancing CO_2 uptake in winter and in lowering ocean pCO_2 in summer
- The sensitivity of the seasonal carbon cycle increases under higher CO_2 emissions

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Abstract

One potentially scalable method to remove CO_2 from the air is ocean alkalinity enhancement (OAE), which works to lower surface ocean partial pressure (pCO_2) and accelerate CO_2 sequestration and durable storage. This study explores how OAE might affect the seasonal carbon cycle, which plays a key role in the ocean's annual CO_2 uptake. By analysing earth system model simulations of OAE implemented continuously at the European coastline until 2100 under low and high climate forcing, it was found that: when carbon cycle seasonality is temperature-driven, a) OAE enhances CO_2 uptake in winter, when it is naturally strongest, and it reduces ocean pCO_2 in summer, when it is naturally highest; b) higher CO_2 emissions increase the sensitivity of the seasonal carbon cycle; c) a region with a shallow bathymetry and well-mixed waters may be ideal for implementing OAE due to fast air-sea CO_2 equilibration.

Short summary

While reducing emissions, technologies are being developed to sequester carbon dioxide (CO_2) from the air. Among the proposed options is ocean alkalinity enhancement (OAE), which works to lower the CO_2 concentration in seawater and accelerate its uptake from the atmosphere as a compensatory effect. As seasonality is important for the annual air-sea CO_2 exchange, this research investigates OAE impacts on the seasonal carbon cycle analysing outputs from a numerical earth system model.

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1 Introduction

The ocean constitutes a valuable resource for climate stabilisation, absorbing much of the earth's excess heat and storing vast amounts of carbon in its interior and deep waters (Friedlingstein et al., 2022; Scott-Buechler & Greene, 2019). Thus, research on marine carbon dioxide removal (CDR) has been expanding, focusing on the use of wetlands, continental shelves and the open ocean to enhance natural CO_2 removal processes. One marine CDR method under investigation is ocean alkalinity enhancement (OAE), which aims to accelerate the ocean CO_2 uptake through weathering, namely the breakdown of rocks and minerals by water-induced chemical reactions whereby atmospheric CO_2 is consumed and eventually stored in the ocean for millenia.

OAE can be realised by releasing alkaline minerals or solutions at the ocean surface, which would chemically convert aqueous CO_2 ($CO_2(aq)$) into stable bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions, that together constitute the dissolved inorganic carbon (DIC) pool. This process would lower the ocean CO_2 partial pressure (pCO_2) and allow for additional CO_2 uptake from the atmosphere to restore the altered equilibrium. Additionally, by increasing the ocean's buffering capacity, OAE would have the benefit of temporarily reducing seawater acidification.

CO_2 seasonality is a major component of the annual net ocean flux. It is mainly controlled by sea surface temperature (SST), its thermal component, and DIC, its biophysical component (Fassbender et al., 2022). SST acts on the chemical solubility of gases in seawater, favouring CO_2 dissolution in winter and CO_2 outgassing in summer (Williams & Follows, 2011). Conversely, DIC leads to CO_2 loss in winter, when enhanced vertical mixing and organic matter (OM) respiration increase carbon content at the top layer, and to CO_2 uptake in summer, when OM production prevails and reduces surface DIC. As SST and DIC are counteracting drivers (Lerner et al., 2021; Gallego et al., 2018, Takahashi et al., 2002), the one that dominates determines the ocean's role as either a net annual CO_2 source or sink at a given location.

Changes to the CO_2 flux seasonality can further perturb the ocean carbon cycle, including earlier calcium carbonate undersaturation (Kwiatkowski et al., 2022) and intensified ocean acidification (Sasse et al., 2015), other than acting upon inter-annual variability patterns (Rustogi et al., 2023). Moreover, the ocean pCO_2 seasonal cycle is expected to increase due to rising atmospheric CO_2 concentrations and a higher oceanic CO_2 background, independently of the seasonal driver (Gallego et al., 2018).

Although OAE has been widely investigated to account for theoretical benefits and challenges, little attention has been given to its effects on the seasonal carbon cycle. For example, OAE could cause asymmetrical or phase shifts to the air-sea CO_2 flux, or alter seasonal extrema. These modifications could in turn affect the ocean's net annual uptake,

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with potential reflections on marine ecosystems at different scales. Additionally, while the atmosphere reacts to system stimuli at short timescales, the ocean system can take several seasons to respond (Salt et al., 2013) and understanding such time lags is necessary to account for OAE impacts. Lastly, OAE efficiency would likely be influenced by changes to the Revelle factor, which quantifies the ocean's sensitivity to pH changes resulting from increasing atmospheric CO_2: the lower the Revelle factor, the larger the seawater buffering capacity against CO_2 perturbations (Egleston et al., 2010). For example, Schwinger et al. (2024) found that, per unit of alkalinity addition, higher atmospheric CO_2 drives larger ocean uptake mainly because of the associated chemical efficiency.

To address these knowledge gaps, we explored 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). Our study aims to (a) analyse the impacts of OAE on seasonal carbon cycle components, and (b) evaluate the influence of the background climate scenario on such outcomes.

2 Materials and Methods

2.1 Earth System Model

The simulations used in this manuscript were run using the Flexible Ocean and Climate Infrastructure (FOCI) ESM (Matthes et al., 2020). FOCI consists of an atmosphere–ocean–sea ice general circulation model with a surface land component, coupling the Nucleus for European Modelling of the Ocean (NEMO3.6, Madec and The NEMO Team, 2015) for ocean and sea-ice, the Jena Scheme for Biosphere–Atmosphere Coupling in Hamburg (JSBACH; Brovkin et al., 2013) for the land, and ECHAM6.3-HAM2.3-MOZ1.0 (ECHAM6-HAMMOZ; Schultz et al., 2018) for the atmosphere. The ocean is divided into 46 vertical layers with a horizontal resolution of 1/2° and the atmosphere is composed of 95 vertical layers with a horizontal resolution of ~1.8°.

In addition to simulating the land carbon cycle, FOCI incorporates the Model of Oceanic Pelagic Stoichiometry (MOPS) (Kriest & Oschlies, 2015) to enable the representation of marine biogeochemical processes and the ocean carbon cycle. MOPS resolves biological dynamics such as phytoplankton carbon uptake and remineralisation, calcite formation and dissolution (Chien et al., 2022).

In FOCI, both alkalinity and DIC agree well with observations, while still showing a positive bias at the surface and a negative bias below 3000 meters of depth (Chien et al., 2022). Most DIC variations are due to OM build-up and CO_2 flux variations, while alkalinity is a prognostic tracer simulated as a combination of biological sources and sinks with:

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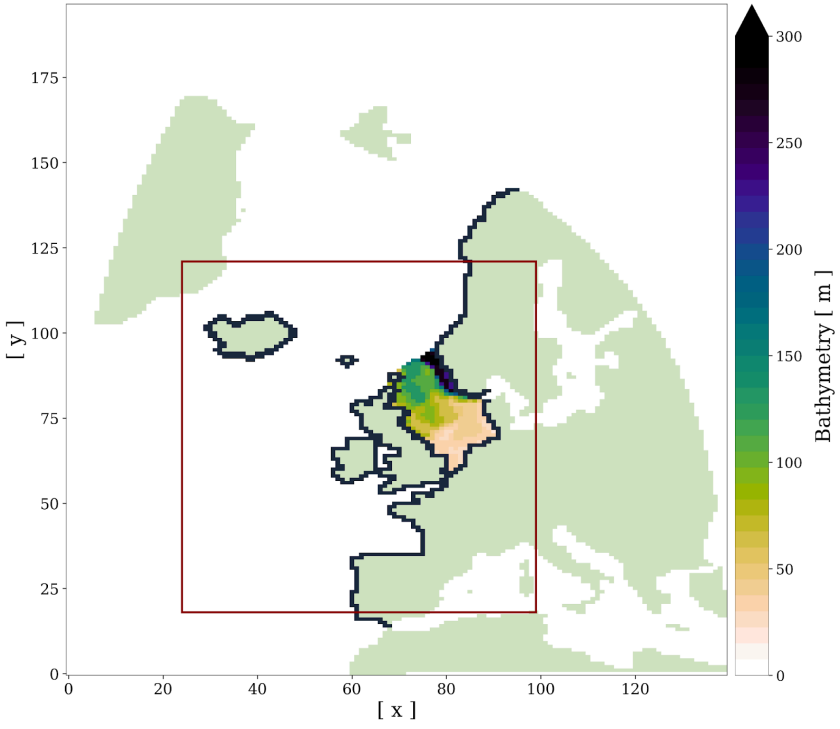
nitrate and phosphate supply as sinks, calcium carbonate production and dissolution as sink and source, respectively, and OM formation and remineralisation as sink and source, respectively (Chien et al., 2022).

2.1 Experimental design

A 1500-year spin-up was carried out with 'physics-only' FOCI, followed by a 500-year spin-up including MOPS (Chien et al., 2022). Then, historical simulations were run from 1850 to 2014, when the SSPs begin (Riahi et al., 2017). All spin-ups, baseline simulations and forcings adhered to the CMIP6 protocol (O'Neill et al., 2016). In order to investigate the role of the climate scenario on OAE application, a low- and high-emission SSP have been selected, namely SSP1-2.6 and SSP3-7.0. Simulations were run in emission-driven mode, such that atmospheric carbon is exchanged with the ocean and the terrestrial biosphere.

Figure 1: Spatial implementation of OAE in European waters. The black strip indicates a 50-km-wide zone of alkalinity addition, while the red rectangle marks the study area analysed in this manuscript. The map also shows the bathymetry of the North Sea, identified as a key hotspot region in this analysis.



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In the OAE simulations, alkalinity is added continuously and uniformly along a 50-km-wide strip of the European coastline, with the exclusion of the Baltic and Mediterranean seas (fig. 1). OAE is applied from 2025 to 2100, with linear increase over the first decade of addition (2025-2034), until the alkalinity equivalent of 1 Gt y-1 of fast-reacting calcium hydroxide ($Ca(OH)_2$) is reached. From 2035, this amount, equal to 1.4 μmol C m-2 y-1, is held constant until the end of the century.

Theoretically, $Ca(OH)_2$ consumes two moles of atmospheric CO_2 and produces one mole of calcium (Ca^{2+}) and two moles of bicarbonate, therefore increasing alkalinity by a factor of two (eq. (1)) (Chien et al., 2022):

$$Ca(OH)_2 + 2CO_2 \leftrightarrow Ca^{2+} + 2HCO_3^- \quad (1)$$

2.3 Data processing

The global output data delivered by FOCI was sliced to the European region, depicted by the red rectangle in fig. 1. This helps maintain some focus beyond the European coastline without diluting the OAE signal, as Palmiéri & Yool (2024) showed that part of the OAE-driven carbon uptake can happen far from the implementation region. Our analysis compares the area of coastal addition (black line in fig. 1), which offers details on regime shifts taking place at the epicenter of the domain, with the European region (including its coastline), which measures how the European system as a whole might respond to OAE.

Assuming that the most visible baseline-to-OAE differences are detected towards the end of the century, the annual cycle averaged over the last simulation decade (2090-2099) is considered here. While ocean pCO_2 and the CO_2 flux are written out only for the surface, alkalinity is calculated over all 46 FOCI ocean layers. Thus, the variable was vertically averaged over a seasonally- and scenario-dependent mixed layer depth (MLD) (also a FOCI output variable defined from potential density), which is the region in direct contact with the atmosphere. The alkalinity that is subducted below the MLD is assumed not to induce CO_2 uptake by the ocean on short timescales (He & Tyka, 2023).

3 Results

3.1 The baseline seasonal state in the study area

Being a continental shelf pump, the North Sea (NS) plays an important role in carbon uptake by transferring atmospheric CO_2 into interior waters and ultimately to the open

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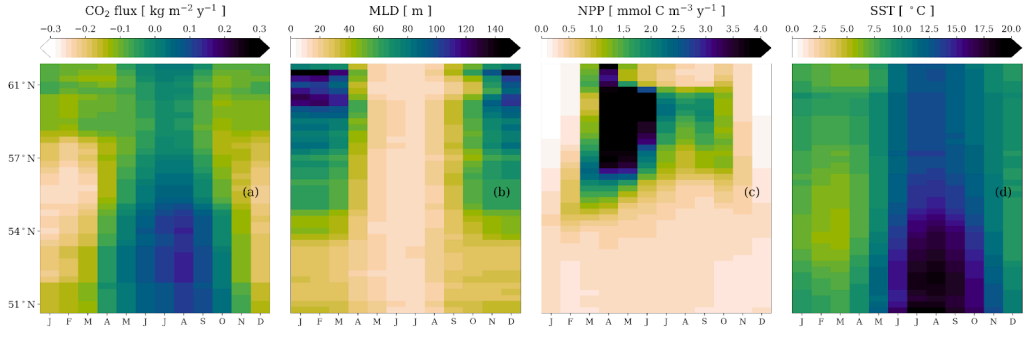
ocean (Prowe et al., 2009). Furthermore, this is the region where the OAE-driven seasonal change signal is strongest in our model. To provide context for interpreting the results, we thus analyse the SSP1-2.6 baseline seasonal state in the NS for the CO_2 flux (fig. 2a) and for its driving variables: MLD (fig. 2b), surface net primary production (NPP) (fig. 2c), and SST (fig. 2d).

In line with previous research, the seasonal air-sea CO_2 flux in the study area is characterised by two biogeochemical provinces, one in the North and the other in the South (Thomas et al., 2004). Biology dominates in the seasonally-stratified northern NS, where winter mixing deepens the mixed layer (fig. 2b) and replenishes surface nutrients. With the onset of spring stratification, the resulting shallow MLD retains nutrients in the euphotic zone, supporting high NPP (fig. 2c) and sequentially driving CO_2 uptake (fig 2a). Accumulated OM then sinks below the surface layer, where remineralisation can happen far from atmospheric contact. At this location, CO_2 sequestration through carbon fixation outweighs temperature-driven outgassing, turning the area into a strong carbon sink (Salt et al., 2013; Prowe et al., 2009).

Figure 2: Hovmöller diagram of the zonally-averaged North Sea section for the SSP1-2.6 baseline seasonal cycle of (a) the CO_2 flux, (b) mixed layer depth (MLD), (c) surface net primary production (NPP), and (d) sea surface temperature (SST) over the 2090-2099 mean. In the CO_2 flux plot, negative values indicate ocean uptake.



In the southern NS and the adjacent European continental shelf, the air-sea CO_2 exchange is primarily controlled by SST (fig. 2d) (Salt et al., 2013). Due to the shallow NS bathymetry (fig. 1) and limited MLD variation (fig. 2b), a well-mixed water column is created year-round. This prevents the seasonal build-up and re-entrainment of nutrients remineralised below the surface during summer, thereby limiting new NPP (fig. 2c). The southern NS is a region of weak CO_2 source to the atmosphere (fig. 2a), as the OM

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production and remineralisation happen within the same surface compartment, where CO_2 can easily be exchanged with the atmosphere, and community respiration outweighs photosynthetic activity (Artioli et al., 2012, Prowe et al., 2009, Thomas et al., 2004).

3.2 OAE-driven modifications to the seasonal carbon cycle

For the European average in SSP1-2.6 (fig. 3a), baseline surface alkalinity has lowest values in summer and highest values in winter, with respective extremes of 2198 and 2209 μmol kg-1. With OAE, alkalinity increases throughout the year: SSP1-2.6 baseline values are higher than SSP3-7.0 (fig. 3b), although OAE increases surface alkalinity relatively less than under high emissions. Under both scenarios, the largest change happens in August.

At the coastline (fig. 3g, h), OAE increases surface ocean alkalinity up to 2672 μmol kg-1 in SSP1-2.6 and 2685 μmol kg-1 in SSP3-7.0, both in summer. Furthermore, the amplitude of the seasonal cycle increases slightly compared to the baseline, amounting to 108 μmol kg-1 and to 138 μmol kg-1 in the low- and high-emission scenario, respectively.

Under both scenarios and in both coastal and European waters, alkalinity addition reverses its surface seasonal cycle, with summer values exceeding winter values. While under natural conditions, alkalinity increases with depth, and winter mixing helps replenish the upper ocean from deeper layers, in the OAE simulations, alkalinity is added at the surface, and stronger vertical stratification in summer leads to greater alkalinity retention in the top layer.

Figure 3: Seasonal cycle averaged over 2090-2099 for surface alkalinity, ocean pCO_2, and the CO_2 flux, with the OAE-baseline difference depicted by the green line. From left to right, columns indicate the European average (top) in SSP1-2.6 (a, c, e) and in SSP3-7.0 (b, d, f), and the coastline average (bottom) in SSP1-2.6 (g, i, k) and in SSP3-7.0 (h, j, l). In the CO_2 flux plots, negative values indicate ocean uptake.

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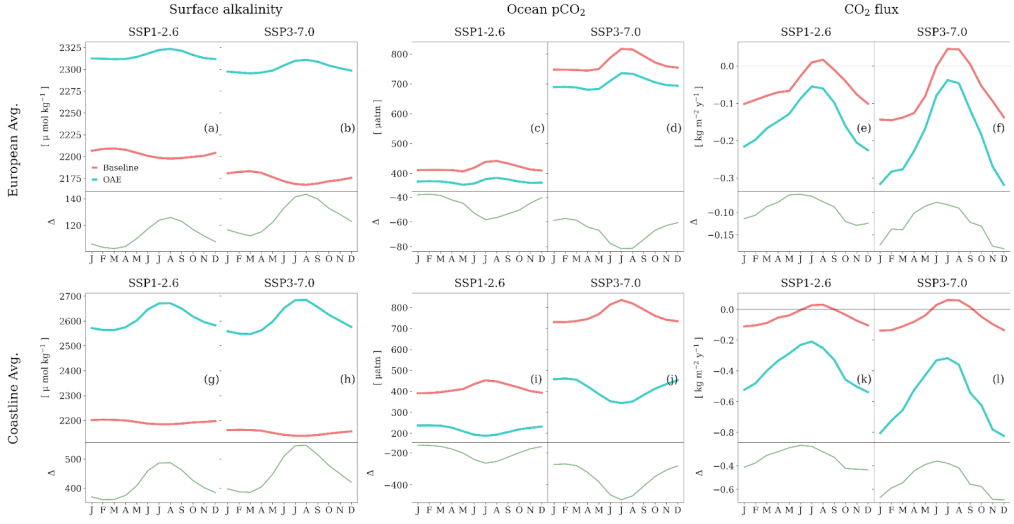

Under both SSPs, the MLD-averaged alkalinity spatial pattern reveals strongest variation in the southern NS as well as by the UK coastline, where the seasonal amplitude grows strongly. In SSP3-7.0 (fig. 4c), the seasonal amplification signal extends over a slightly wider area than in SSP1-2.6 (fig. 4a), while open ocean regions like Iceland, Spain and Norway show less strong changes compared to the baseline.

For ocean pCO_2, the European average in SSP1-2.6 (fig. 3c) is characterised by lowest and highest values in May and August, respectively, with a mean seasonal amplitude of 35 µatm. Ocean pCO_2 minima are identified in spring as a result of phytoplankton bloom and consequent high NPP (fig. 2c), whereby CO_2 is drawn down by photosynthetic fixation. In the OAE simulation, ocean pCO_2 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.

At the coastline, ocean pCO_2 is directly influenced by the OAE-driven reversal of the alkalinity seasonal cycle: highest (lowest) summer (winter) values in the baseline become lowest (highest) in the OAE scenario. In SSP1-2.6 (fig. 3i), ocean pCO_2 decreases by about 200 µatm, and the amplitude is reduced by 11 µatm. In SSP3-7.0 (fig. 3j), OAE doubles the reduction of ocean pCO_2 values compared to SSP1-2.6 and values become similar to the low warming baseline, though the amplitude is enhanced by 11 µatm.

OAE reduces surface ocean pCO_2 in all cases, with the strongest variation occurring in summer, when natural ocean pCO_2 reaches its peak. This indicates that, in our simulations, alkalinity addition produces the greatest pCO_2 decline during periods of natural CO_2 outgassing. At the European average, this results in a reduction of the seasonal pCO_2 amplitude that is more pronounced under low emissions. Along the coastline, while

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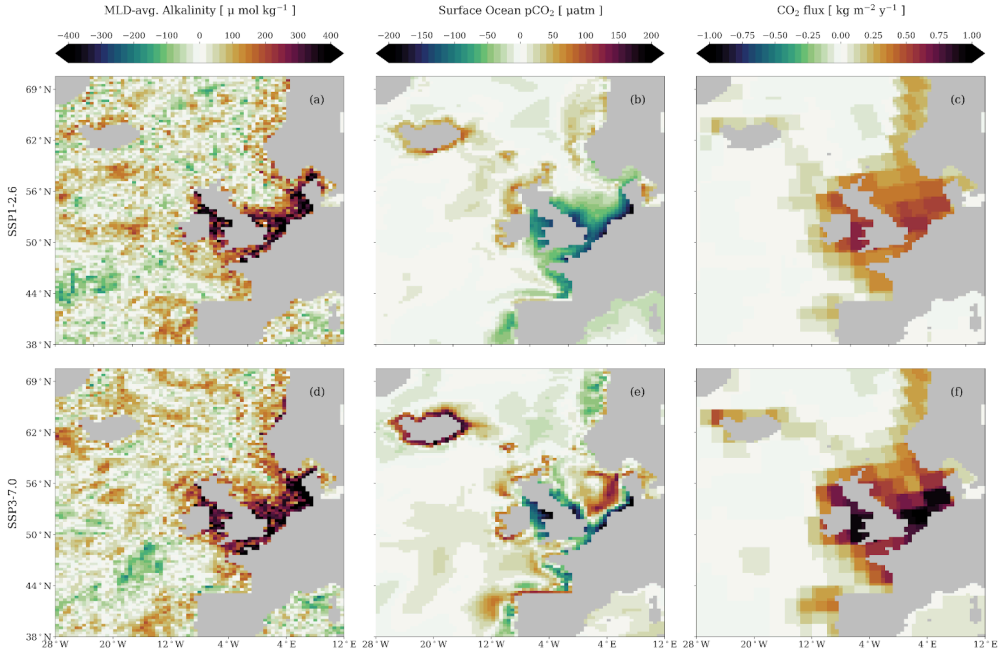
SSP1-2.6 shows an amplitude reduction, SSP3-7.0 leads to an amplitude increase. Thus, while in a low-warming climate, alkalised water becomes less sensitive to DIC fluctuations, higher atmospheric CO_2 partially counteracts the buffering effect driven by alkalinity addition, leading to a higher Revelle factor.

Figure 4: Seasonal amplitude change (OAE - baseline) averaged over 2090-2099 for (a, d) MLD-averaged alkalinity, for (b, e) ocean pCO_2 and for (c, f) the air-sea CO_2 flux. The top row is SSP1-2.6 and the bottom row is SSP3-7.0. CO_2 flux calculations are performed on the atmospheric component of FOCI, which has a coarser resolution than the ocean component.



In SSP1-2.6 (fig. 4b), a distinct spatial pattern of pCO_2 seasonal change is identified, with two diverging geographies: at higher latitudes, including Iceland, the Norwegian and British North-West bank, the seasonal amplitude is slightly more pronounced than the baseline, while at lower latitudes, namely the mainland shoreline and the central-to-southern UK coasts, the seasonal cycle is strongly mitigated. In SSP3-7.0 (fig. 4e), results are magnified in Iceland, in the Southern NS, in the UK and Irish coasts. Exceptions are found in the central NS and Northern Spain, where strong seasonal

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amplification is displayed, and by the Norwegian coast, where the ocean pCO_2 seasonal cycle is reduced.

As for the CO_2 flux, seasonality is driven by temperature in our study area: the system outgasses (takes up) CO_2 in summer (winter), at lowest (highest) chemical solubility, and the largest CO_2 release happens between July and August. Alkalinity addition enhances the CO_2 flux seasonal cycle everywhere and under both warming scenarios, turning the system into a CO_2 sink year-round. CO_2 uptake grows more strongly in winter, meaning that alkalinisation impacts are largest when ocean uptake is naturally highest, and in SSP3-7.0, meaning that the system becomes more sensitive under higher emissions.

For the European average, OAE-induced CO_2 flux amplitude has an average span of 0.171 kg m-2 yr-1 in SSP1-2.6 and 0.281 kg m-2 yr-1 in SSP3-7.0, compared to their respective baselines (0.118 kg m-2 yr-1 and 0.191 kg m-2 yr-1). At the coastline in the OAE-driven SSP1-2.6 simulation, the CO_2 flux seasonal amplitude is 0.329 kg m-2 yr-1, therefore more than doubling the baseline amplitude of 0.114 kg m-2 yr-1. With an amplitude of 0.505 kg m-2 yr-1, the OAE seasonal CO_2 flux in SSP3-7.0 is more than 2.5 times larger than the baseline (0.199 kg m-2 yr-1). Spatially, in SSP1-2.6, the OAE scenario reveals largest CO_2 seasonal flux amplification along the European continental coastline, and the signal remains strong until the connection with the open ocean (fig. 4c). Seasonal amplification is enhanced under high emissions (fig. 4f), especially in the southern NS, at the UK coastline and in North-West Iceland.

5 Discussion

Our results show that significant system perturbations happen within the model domain, especially in close proximity to the alkalinity addition site. However, this manuscript does not address alkalised water that is subducted before air-sea equilibration is complete, and uncertainty remains on whether that water could resurface to drive CO_2 uptake elsewhere. In Palmiéri & Yool (2024), for example, it was estimated that about 50% of CO_2 uptake favoured by global coastal OAE happened remotely from the alkalinity injection sites.

In agreement with Schwinger (2022), OAE works to amplify the CO_2 seasonal flux, prompting greater carbon uptake during winter. This is because OAE effects are larger in the season where higher CO_2 drawdown occurs naturally. Additionally, OAE-induced modifications to ocean pCO_2 are highest in the season where the associated seasonal driver reduces the ocean CO_2 sink potential, as alkalised water minimises pCO_2 sensitivity to DIC flux modulations and strengthens the ocean's buffering capacity, thus lowering the Revelle factor. Spatial variations across latitudes may result from contrasting responses

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between semi-enclosed regions and the open ocean, or from differences in the local seasonal driver of the carbon cycle.

Both in European waters and at the coastline, highest alkalinity is recorded between the end of summer and the onset of autumn, but the largest CO_2 uptake occurs in winter, thus introducing a response lag of a few weeks. Jones et al. (2014) note that air-sea equilibration can take from a few months to even years to complete, depending on regional properties. 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.

In the OAE simulations, the seasonal cycle of surface alkalinity is reversed under both SSPs, especially in summer. However, its absolute levels increase relatively more in SSP3-7.0 compared to SSP1-2.6 because vertical stratification, and therefore surface retention, is larger in a high CO_2 world. Ocean pCO_2 absolute values show a less significant decline in SSP1-2.6 compared to SSP3-7.0, although the amplitude compression signal is stronger in the former. Exceptionally, the SSP3-7.0 coastline amplitude is enhanced, as its sensitivity due to rising temperatures outweighs reduced sensitivity due to alkalinity addition. For the CO_2 flux, since the seasonal amplification is stronger in SSP3-7.0, higher background emissions makes the system more susceptible to external alterations. As noted by Nagwekar et al. (2024), this is probably more linked to the ocean carbonate chemistry, which becomes more sensitive under high CO_2 emissions, than to the background atmospheric CO_2 concentration (Schwinger et al., 2024).

Our results indicate that OAE-induced impacts on the seasonal cycle of ocean pCO_2 and the CO_2 flux are spatially- and scenario-dependent. Spatially, the most affected area is the North Sea, especially its southern part, and the coastal ocean between the UK and Ireland, which show pronounced seasonal alterations. A shallow, well-mixed and partially-enclosed sea allows for alkalinity to accumulate at the surface, rather than being lost due to subduction to deeper layers or advection to the open ocean (Liu et al., 2025; Wang et al., 2023). As for the influence of the climate scenario, the seasonal sensitivity of the ocean carbon cycle increases with larger CO_2 emissions and OAE alone is less efficient in mitigating seasonal amplitude changes in the high-emissions scenario compared to the low-emission scenario. Furthermore, higher atmospheric CO_2 concentrations, which have an amplifying effect on the thermally-driven component of ocean pCO_2, lead to an overall expansion of the CO_2 seasonal cycle due to stronger chemical leverage. This outcome is exacerbated by OAE implementation due to the scenario-dependent chemical efficiency of OAE (Schwinger et al., 2024).

6 Conclusions

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This study addressed the OAE-driven variations to the seasonal carbon cycle in European waters under low and high warming, contributing to the understanding of CO_2 intra-annual variability when continuous coastal OAE is applied. It was found that, in a region of temperature-driven seasonality, (a) OAE enhances the CO_2 uptake in winter, when it is naturally strongest, and it reduces ocean pCO_2 in summer, when it is naturally highest; (b) the sensitivity of the seasonal carbon cycle increases under higher emissions, enhancing the CO_2 flux seasonal amplification and contrasting the pCO_2 seasonal dampening; (c) locations like the southern North Sea could be ideal to implement OAE, as a shallow bathymetry and intense mixing can hasten the CO_2 gas transfer at the air-sea interface, at least as far as the equilibration timescale is shorter than the surface water mean residence time.

Some limitations and future recommendations can be drawn from this study. Firstly, while freshwater input from rivers is modelled in FOCI, riverine alkalinity is not accounted for, limiting the reliability of absolute values. Alkalinity in the Baltic Sea, for example, is poorly resolved by FOCI, which could have an impact on the NS boundary conditions. Additionally, as river runoff features are deeply seasonal, implementing such processes would improve the accuracy of future simulations. Secondly, our analysis does not separate the CO_2 flux into its thermal and biological element, therefore missing to discern the influence that each has in altering the CO_2 seasonal cycle. Given the significance of temperature variability in the southern NS, calculating both terms individually could provide further insight into their seasonal role under OAE deployment. Lastly, our OAE simulations picture a highly idealised scenario, which is unlikely to become a real-world case. Other, more realistic OAE techniques should be explored, such as pulsed or point-source experiments. Building on these simulations, further investigation is therefore recommended to set the premises for a conscious large-scale OAE application.

7 Author contribution

Conceptualisation: C. Ciscato, D. P. Keller; Performing model simulations: T. P. Kemena; Data curation: C. Ciscato, D. P. Keller; Formal analysis: C. Ciscato; Investigation: C. Ciscato; Methodology: D. P. Keller, T. P. Kemena; Supervision: D. P. Keller; Validation: D. P. Keller; Visualisation: C. Ciscato; Writing – original draft: C. Ciscato; Writing – review & editing: C. Ciscato, D. P. Keller, N. Mehendale, T. P. Kemena, S. Avrutin.

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9 Data availability

The datasets used in this manuscript are available at this Zenodo link (https://zenodo.org/records/13935197?token=eyJhbGciOiJIUzUxMiJ9.eyJpZCI6Ijg2ZWViNjU4LWMyZDYtNGFmZC04MzI0LWUxMmE5YTNhMzdhNyIsImRhdGEiOnt9LCJyYW5kb20iOiIyODIyODFjZmUwZTk2MzJjOTcxNGM2ZWMzMWNkNDYwMyJ9.snS8fH7EYBkEYYLP9xUI_P2V4L4HUKBYEi61fFGDd43WwMskAWQBsncfdpBMYii_TpWstwKQbsFSCF2K__F4oQ).

The code underlying this study is openly available at the following GitHub repository: 2026 ciscato oae seasonality (https://github.com/chiaraciscato/2025_ciscato_oae_seasonality) .

10 Referencess

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