

1 Impacts of Simulated Coastal Ocean Alkalinity Enhancement on the Seasonal Carbon Cycle in
2 European Waters under a Low- and a High-Emission Scenario
~~3 Ocean Alkalinity Enhancement on the Seasonal Cycle of the Air-Sea CO₂ Flux and Surface~~
~~4 Ocean pCO₂ in European Waters under a Low- and a High-Emission Scenario~~

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6 Chiara Ciscato ^{1,2}, Neha Mehendale ^{2,4}, Tronje P. Kemena ², Sandy Avrutin ², David P. Keller ^{2,3}

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8 ¹ CMCC Foundation - Euro-Mediterranean Center on Climate Change (Italy)

9 ² GEOMAR Helmholtz Centre for Ocean Research, Kiel (Germany)

10 ³ now at Carbon to Sea Initiative, Washington, DC (USA)

11 ⁴ Institute for Environmental Physics, University of Bremen (Germany)

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15 Key Points:

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17 • Ocean Alkalinity Enhancement (OAE) aims to increase the ocean's potential to sequester and
18 store atmospheric CO₂
19 • Due to summer retention, surface OAE reverses the seasonal cycle of alkalinity and it decreases
20 ocean pCO₂, turning the system into a year-round carbon sink
21 • OAE drives the strongest CO₂ uptake enhancement in winter, while high emissions amplify this
22 signal
~~23 Ocean Alkalinity Enhancement (OAE) aims to increase the ocean's potential to sequester~~
~~24 and store atmospheric CO₂~~
~~25 In our study area, OAE effects are strongest in enhancing CO₂ uptake in winter and in lowering~~
~~26 ocean pCO₂ in summer~~
~~27 The sensitivity of the seasonal carbon cycle increases under higher CO₂ emissions~~

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30 Corresponding author: Chiara Ciscato, chiara.ciscato@cmcc.it

Abstract

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.

~~One potentially scalable method to remove CO₂ from the air is ocean alkalinity enhancement (OAE), which works to lower surface ocean partial pressure (pCO₂) and accelerate CO₂ 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 CO₂ 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 CO₂ uptake in winter, when it is naturally strongest, and it reduces ocean pCO₂ in summer, when it is naturally highest; b) higher CO₂ emissions increase the sensitivity of the seasonal carbon cycle; c) regions with shallow bathymetry and well-mixed waters may be ideal for implementing OAE due to fast air-sea CO₂ equilibration.~~

Short summary

Ocean Alkalinity Enhancement (OAE) is an ocean carbon dioxide removal method with large-scale potential. Using an Earth System Model, we explored the effects of continuous coastal OAE application on the seasonal carbon cycle under low and high greenhouse gas emissions. We found that surface stratification retains higher alkalinity over summer, reducing the ocean pCO₂ and turning the region into a year-round carbon sink. Additionally, high emissions lower the ocean's buffering capacity and increase the air-sea CO₂ uptake in winter.

~~While reducing emissions, technologies are being developed to sequester carbon dioxide (CO₂) from the air. Among the proposed options is ocean alkalinity enhancement (OAE), which works to lower the CO₂ concentration in seawater and accelerate its uptake from the atmosphere as a compensatory effect. As seasonality is important for the annual air-sea CO₂ exchange, this research investigates OAE impacts on the seasonal carbon cycle analysing outputs from a numerical earth system model.~~

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 CO₂ removal processes. 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 the ocean for a long time. ~~One marine CDR method under investigation is ocean alkalinity enhancement (OAE), which aims to accelerate the ocean CO₂ uptake through weathering, namely the breakdown of rocks and minerals by water-induced chemical reactions whereby atmospheric CO₂ is consumed and eventually stored in the ocean for millennia.~~ Specifically, OAE would enhance natural weathering, namely the breakdown of rocks and minerals by water-induced chemical reactions that consume atmospheric CO₂. OAE can be realised by releasing alkaline minerals or solutions at the ocean surface, which would chemically convert aqueous CO₂ (CO₂(aq)) into stable bicarbonate (HCO₃⁻) and carbonate (CO₃²⁻) ions, that together constitute the dissolved inorganic carbon (DIC) pool. This process would lower the ocean CO₂ partial pressure (pCO₂) and allow for additional CO₂ uptake from the atmosphere to restore the altered equilibrium. Additionally, by increasing the ocean's buffering capacity, OAE would have the additional benefit of temporarily reducing seawater acidification.

CO₂ seasonality is a major contributor to the annual net ocean flux, mainly controlled by sea surface temperature (SST), its thermal component, and DIC, its biophysical component (Fassbender et al., 2022). Variations in SST act on the chemical solubility of gases in seawater, favouring CO₂ dissolution in winter and CO₂ outgassing in summer (Williams & Follows, 2011). 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. 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 CO₂ source or sink at a given location. ~~CO₂ 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). Variations in SST act on the chemical solubility of gases in seawater, favouring CO₂ dissolution in winter and CO₂ outgassing in summer (Williams & Follows, 2011). Conversely, Variations in DIC lead to CO₂ loss in winter, when enhanced vertical mixing and organic matter (OM) respiration increase carbon content at the top layer, and to CO₂ 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 CO₂ source or sink at a given location.~~

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). ~~Changes to the CO₂ 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 pCO₂ seasonal cycle is expected to increase due to rising atmospheric CO₂ concentrations and a higher oceanic CO₂ 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 CO₂ flux, or alter seasonal extrema. These modifications could in turn affect the ocean's net annual uptake, 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 CO₂: the lower the Revelle factor, the larger the seawater buffering capacity against CO₂ perturbations (Egleston et al., 2010). For example, Schwinger et al. (2024) found that, per unit of alkalinity addition, higher atmospheric CO₂ 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). Alkalinity is a prognostic tracer simulated as a combination of biological sources and sinks, including: nitrate and phosphate supply as sinks, calcium carbonate production and dissolution as sink and source, respectively, and organic matter production and remineralisation as sink and source, respectively (Chien et al., 2022). 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

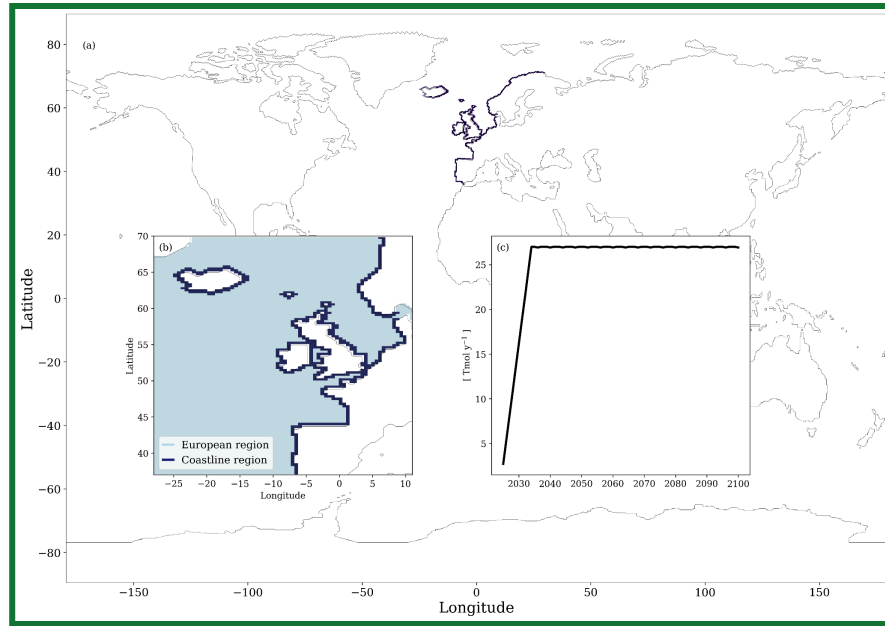
boundary flux (Matthes et al., 2020). Since the CO₂ flux calculation is performed on the less resolved atmospheric grid, sub-atmospheric-grid oceanic gradients are smoothed before the flux is calculated

~~In FOCL, 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 CO₂ flux variations, while alkalinity is a prognostic tracer simulated as a combination of biological sources and sinks with: 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).~~

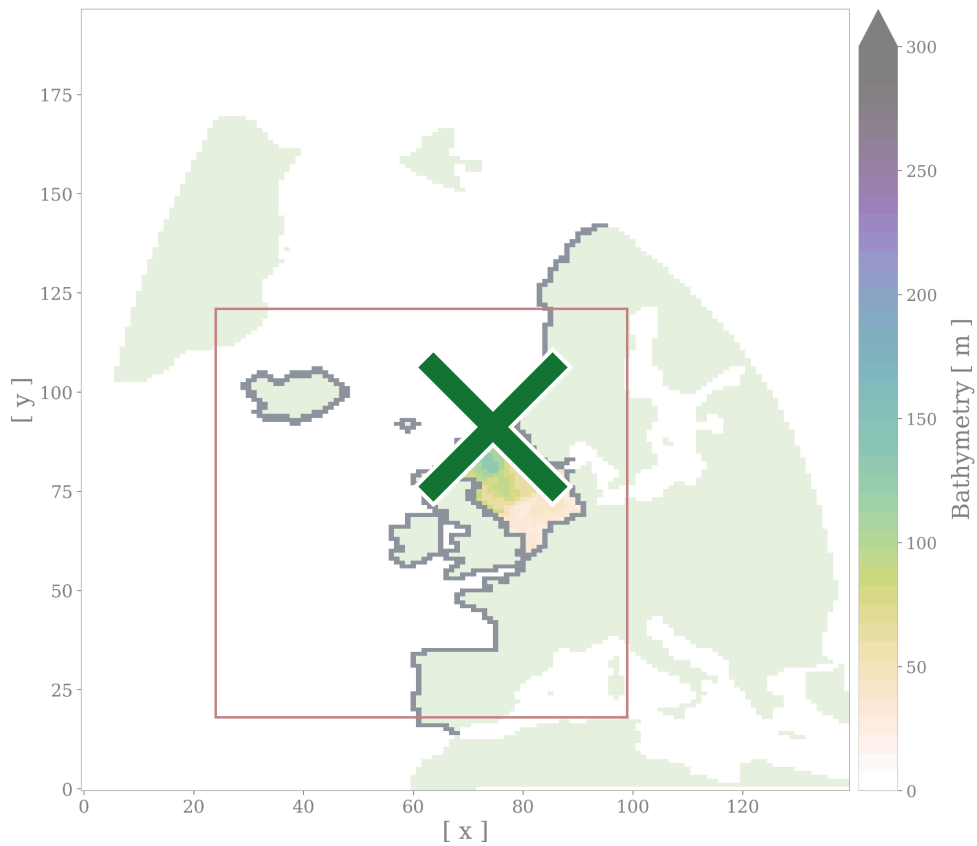
2.1 Experimental design

A 1500-year spin-up was carried out with ‘physics-only’ FOCL, 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, Eyring et al., 2016)(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: (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: 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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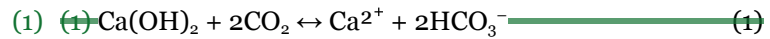
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205 In the OAE runs, alkalinity is introduced continuously and evenly into the surface layer of the
 206 coastal grid cells outlined by the coloured line in Fig. 1a, spanning a vertical depth of roughly 3
 207 meters. As the model runs with a horizontal 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. OAE is applied from 2025 to 2100, with linear increase over the first decade of addition (2025-2034), until the equivalent of 1 Gt y⁻¹ of fast-reacting calcium hydroxide (Ca(OH)₂) is reached. From 2035, this amount, which equals 27 Tmol y⁻¹ of alkalinity (or 44 mol m⁻² y⁻¹), is held constant until the end of the century (Fig. 1c). Theoretically, Ca(OH)₂ consumes two moles of atmospheric CO₂, and it produces one mole of calcium (Ca²⁺) and two moles of bicarbonate, therefore increasing alkalinity by a factor of two (eq. (1)) (Chien et al., 2022): ~~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 m⁻² y⁻¹, is held constant until the end of the century. ¶~~

~~Theoretically, Ca(OH)₂ consumes two moles of atmospheric CO₂ and produces one mole of calcium (Ca²⁺) and two moles of bicarbonate, therefore increasing alkalinity by a factor of two (eq. (1)) (Chien et al., 2022):~~

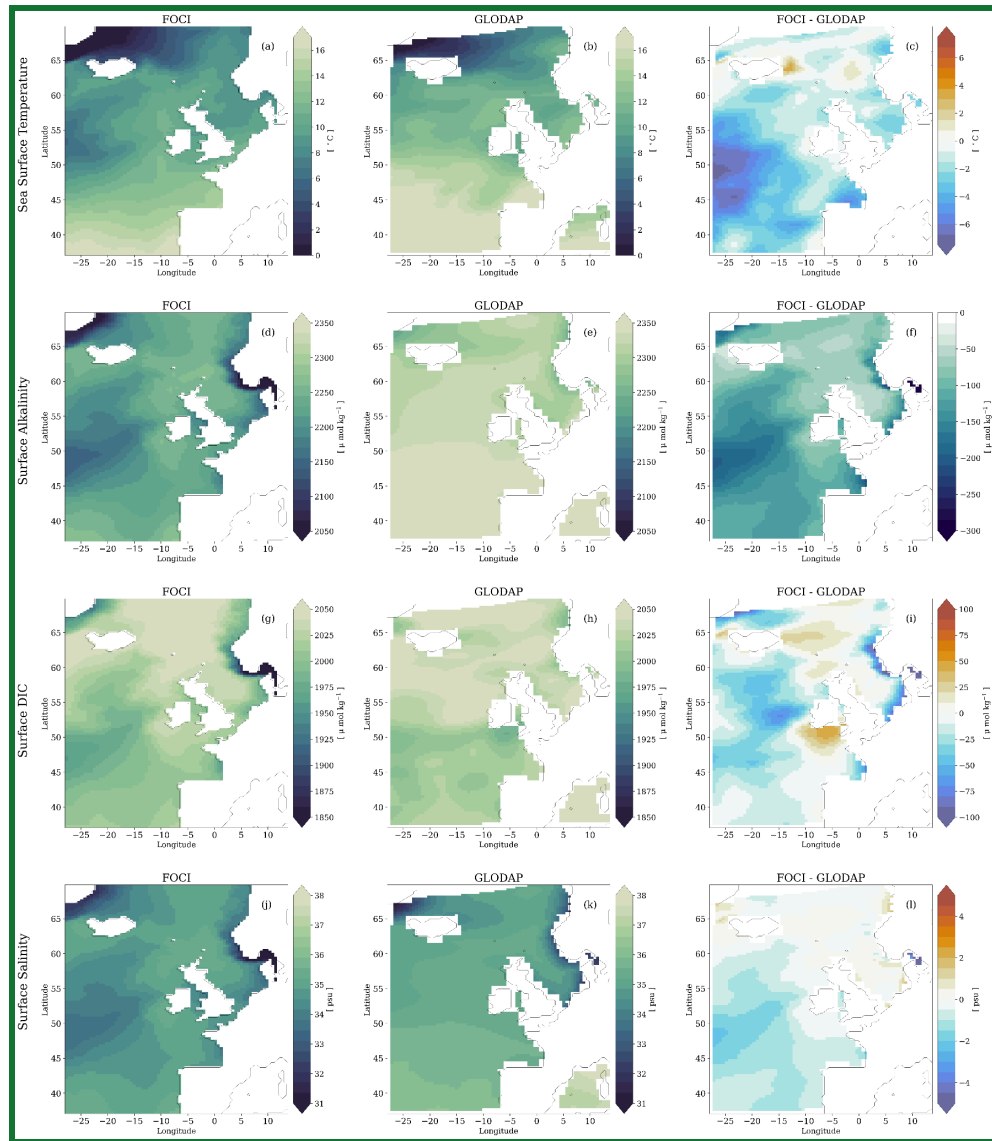


2.3 Regional model validation

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 GLODAPv2 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.

2.4.3 Data processing

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 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. ~~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 $p\text{CO}_2$ and the CO_2 flux are calculated only for the surface, alkalinity is represented 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. ~~While ocean $p\text{CO}_2$ 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). Importantly, the CO_2 flux outputs shown in the Results section are taken from the coarser atmospheric grid.

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 present results for OAE seasonal carbon sequestration potential, defined as the ratio of the seasonal change in CO_2 flux between a run with OAE and a run without OAE, and the amount of monthly added alkalinity carbon equivalent.

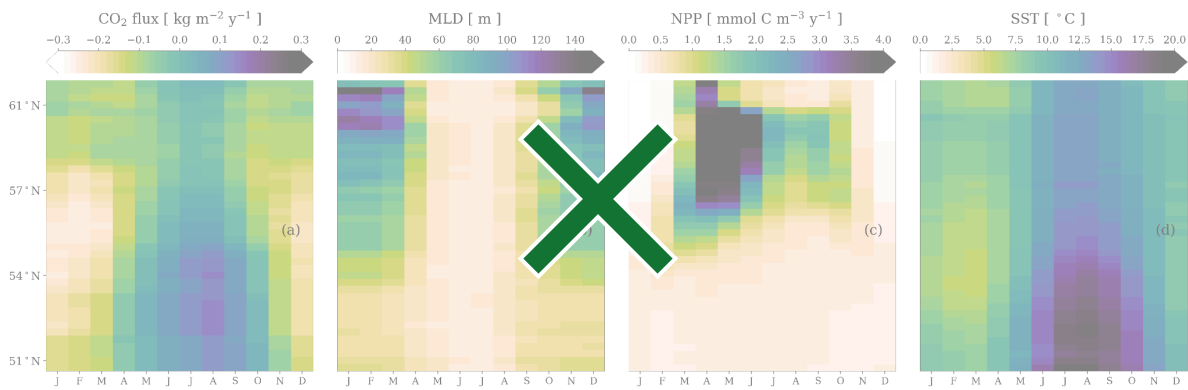
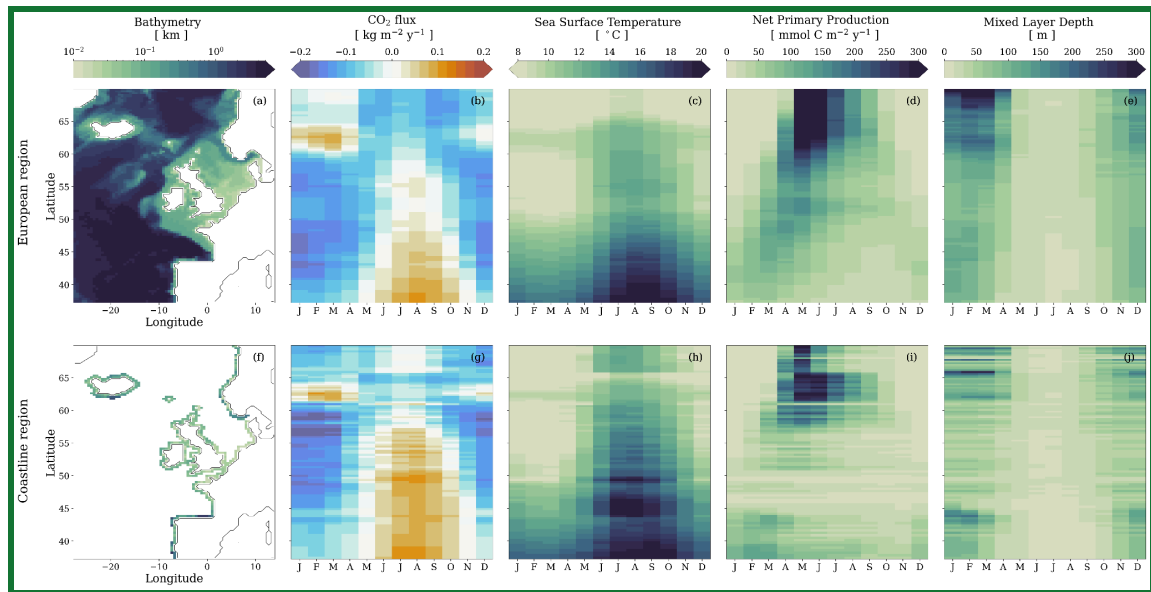
3 Results

3.1 The seasonal state in the control run ~~The baseline seasonal state in the study area~~

As a continental shelf pump, the European region plays an important role in carbon uptake dynamics by transferring atmospheric CO₂ into interior coastal waters and ultimately to the open ocean in the North Atlantic. As outlined above, the CO₂ 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 CO₂ 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). ~~Being a continental shelf pump, the North Sea (NS) plays an important role in carbon uptake by transferring atmospheric CO₂ into interior waters and ultimately to the open 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 CO₂ 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 CO₂ 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 CO₂ uptake (fig. 2a). Accumulated OM then sinks below the surface layer, where remineralisation can happen far from atmospheric contact. At this location, CO₂ 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 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: Hovmöller diagram of the zonally averaged North Sea section for the SSP1-2.6 baseline seasonal cycle of (a) the CO₂ 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 CO₂ flux plot, negative values indicate ocean uptake.~~



For the air-sea CO_2 flux, the European region and the coastline 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 CO_2 uptake happens in winter, when CO_2 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 CO_2 and ingassing is favoured.

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

in the European region, especially between 50° N and 60° N, resulting in a relatively more pronounced CO₂ uptake (outgassing) in winter (summer). In the southern NS and the adjacent European continental shelf, the air-sea CO₂ 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 CO₂ source to the atmosphere (fig. 2a), as the OM production and remineralisation happen within the same surface compartment, where CO₂ 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

Below, we present results on the OAE-driven seasonal changes in alkalinity, surface ocean pCO₂ and the CO₂ flux, focusing on their temporal evolution over the 2090-2099 decade (Fig. 4) as well as on their spatial differences, both vertically (Fig. 5) and horizontally (Fig. 6). Average values for the main carbonate variables are summarised in Table 1.

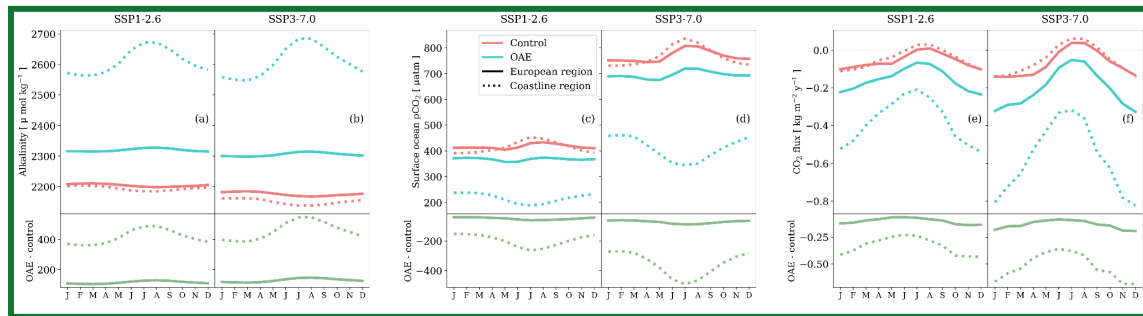
Table 1: Annual minimum and annual maximum values averaged over 2090-2099 for alkalinity, surface ocean pCO₂, the air-sea CO₂ flux, and the mixed layer depth. Results are presented for the European region and the coastline region under both emission scenarios in the control and OAE runs. Note that air-sea 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)

In the European region (Fig. 4a, b), surface alkalinity in the control run has lowest values in summer and highest values in winter, with respective extremes of 2198 μmol kg⁻¹ and 2210 μmol kg⁻¹ in SSP1-2.6, and of 2167 μmol kg⁻¹ and 2184 μmol kg⁻¹ in SSP3-7.0. Seasonal alkalinity follows MLD seasonality, whereby winter mixing deepens the mixed layer, replenishing the surface with high-alkalinity sub-surface waters. In the OAE runs, alkalinity increases throughout the year: while

in SSP1-2.6, control values are higher than in SSP3-7.0, OAE increases surface alkalinity relatively less, especially in summer, where it is increased by $117 \mu\text{mol kg}^{-1}$ and by $130 \mu\text{mol kg}^{-1}$ for the low- and high-emission scenario, respectively. 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 $2209 \mu\text{mol kg}^{-1}$. 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.

Figure 3: Seasonal cycle averaged over 2090-2099 for surface alkalinity in SSP1-2.6 (a) and in SSP3-7.0 (b), for surface ocean $p\text{CO}_2$ in SSP1-2.6 (c) and in SSP3-7.0 (d), and for the CO_2 flux in SSP1-2.6 (e) and in SSP3-7.0 (f), with the respective difference depicted by the green line. Continuous lines represent the European region and dashed lines represent the coastline region. In the CO_2 flux plots, negative values indicate ocean uptake



In the coastline region (Fig. 4g, h), where control alkalinity is similarly highest in winter and lowest in summer, OAE increases surface values up to $2672 \mu\text{mol kg}^{-1}$ in SSP1-2.6 and to $2685 \mu\text{mol kg}^{-1}$ in SSP3-7.0, both in summer. Furthermore, the amplitude of the seasonal cycle increases greatly compared to the control runs, shifting from about $19 \mu\text{mol kg}^{-1}$ to $108 \mu\text{mol kg}^{-1}$ and from $24 \mu\text{mol kg}^{-1}$ to $138 \mu\text{mol kg}^{-1}$ in the low- and high-emission scenario, respectively. As increasing emissions enhance surface warming, higher surface alkalinity in SSP3-7.0 is the result of enhanced vertical stratification, whereby more of the added alkalinity is retained at the top layer. At the coastline (fig. 3g, h), OAE increases surface ocean alkalinity up to $2672 \mu\text{mol kg}^{-1}$ in SSP1-2.6 and $2685 \mu\text{mol kg}^{-1}$ in SSP3-7.0, both in summer. Furthermore, the amplitude of the seasonal cycle increases slightly compared to the baseline, amounting to $108 \mu\text{mol kg}^{-1}$ and to $138 \mu\text{mol kg}^{-1}$ in the low- and high emission scenario, respectively.

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. 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.

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 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.

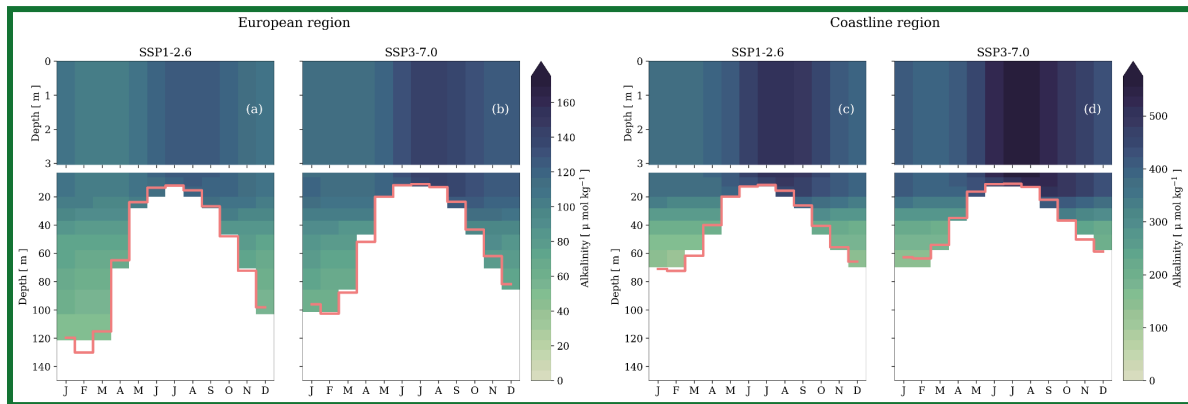
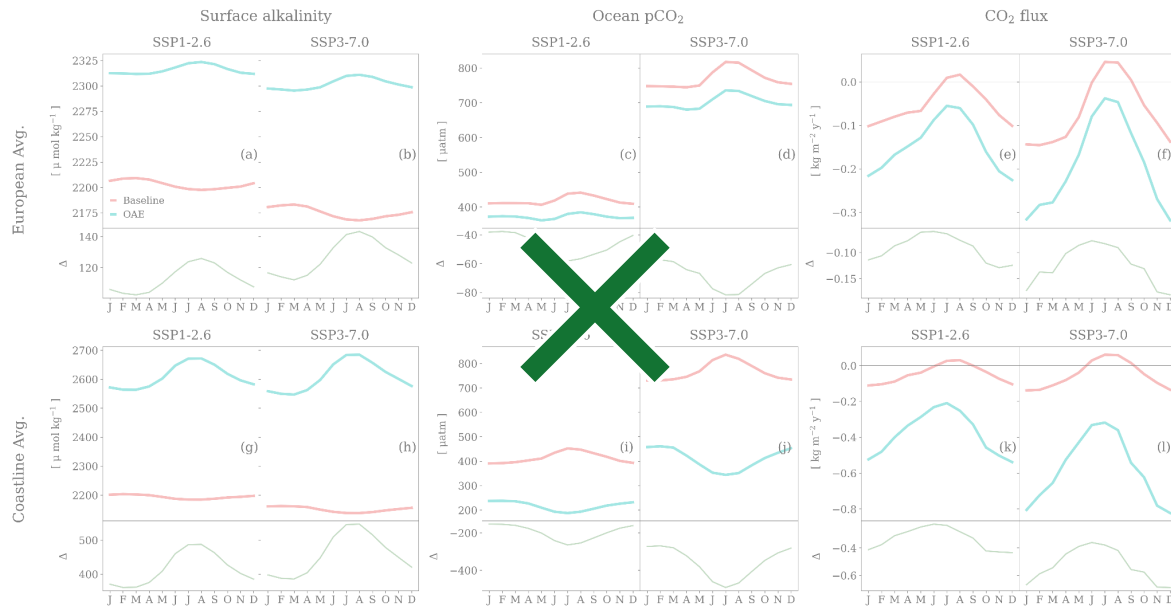


Figure 43: Seasonal cycle averaged over 2090–2099 for surface alkalinity in SSP1 2.6 (a) and in SSP3 7.0 (b), for surface ocean $p\text{CO}_2$ in SSP1 2.6 (c) and in SSP3 7.0 (d), and for the CO_2 flux in SSP1 2.6 (e) and in SSP3 7.0 (f), with the respective difference depicted by the green line. Continuous lines represent the European region and dashed lines represent the coastline region. In the CO_2 flux plots, negative values indicate ocean uptake. Seasonal cycle averaged over 2090–2099 for surface alkalinity, ocean $p\text{CO}_2$, 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 average of the coastline of addition (bottom) in SSP1-2.6 (g, i, k) and in SSP3-7.0 (h, j, l). In the CO₂ flux plots, negative values indicate ocean uptake.



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. 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. 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 off the coasts of Iceland, Spain and Norway show less strong changes compared to the baseline.

With regard to the 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

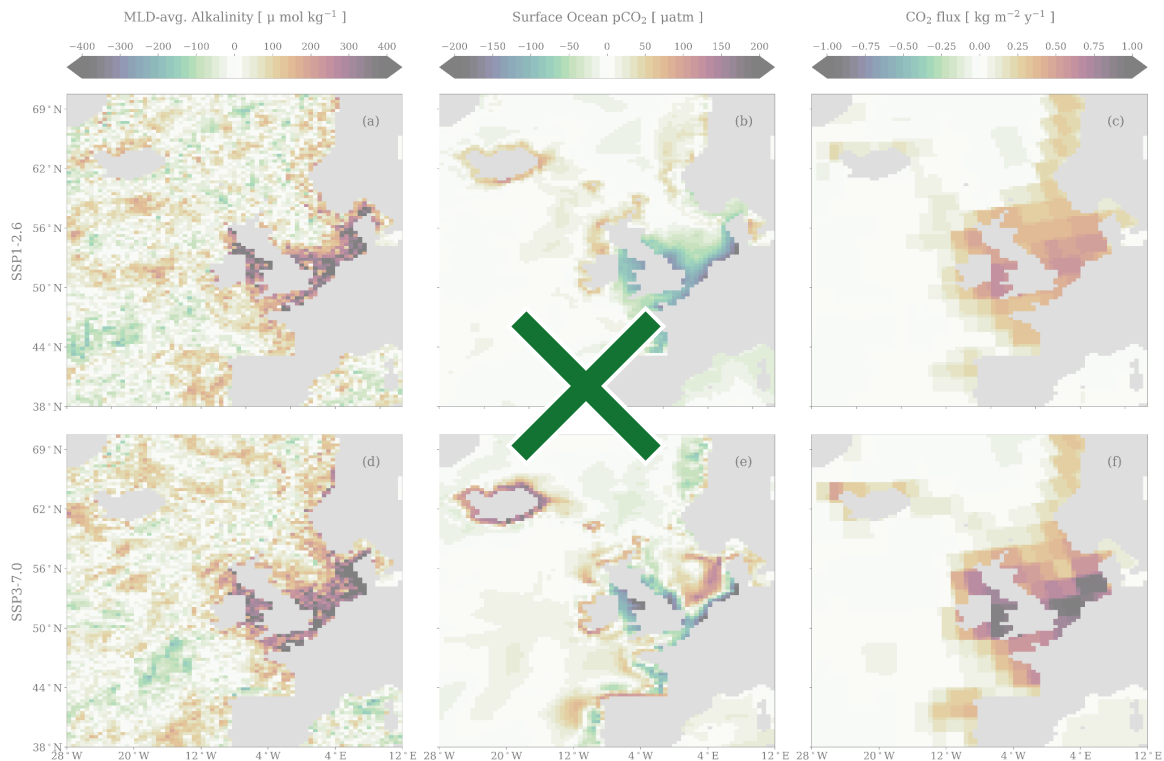
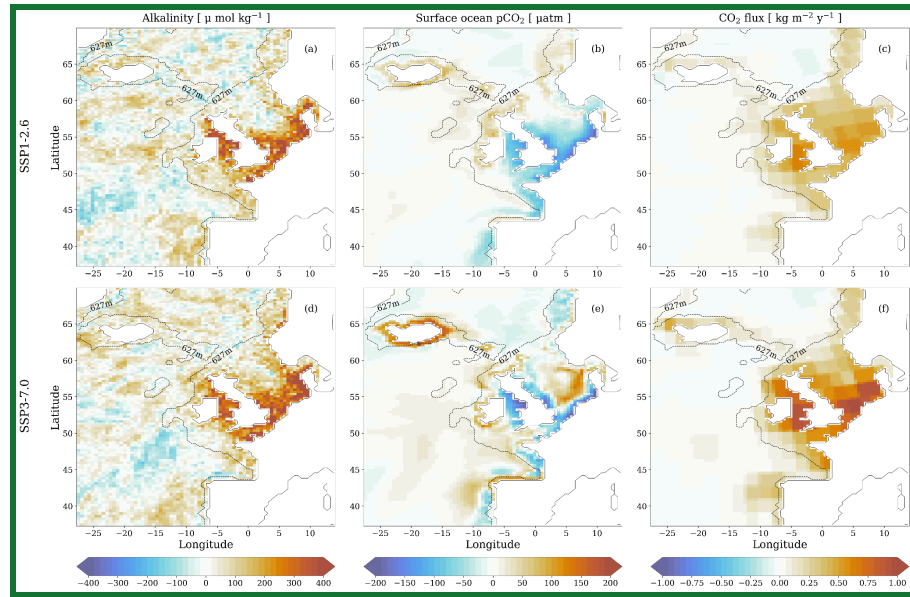
over spring. While in the European region $p\text{CO}_2$ exhibits the same seasonality in both OAE and baseline simulations, in the coastline region, surface ocean $p\text{CO}_2$ is directly influenced by the OAE-driven reversal of the alkalinity seasonal cycle: highest (lowest) summer (winter) values in the control run become lowest (highest) in the OAE run. In SSP1-2.6 (Fig. 4c), the seasonal amplitude of the ocean $p\text{CO}_2$ 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. For ocean $p\text{CO}_2$, 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 $p\text{CO}_2$ 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 $p\text{CO}_2$ 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 $p\text{CO}_2$ 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 $p\text{CO}_2$ 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 $p\text{CO}_2$ 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 $p\text{CO}_2$ in both the European region and in the coastline region, and under both emission scenarios, with the strongest change occurring in summer, when the control runs reach their peak. OAE reduces surface ocean $p\text{CO}_2$ in all cases, with the strongest variation occurring in summer, when natural ocean $p\text{CO}_2$ reaches its peak. This behaviour indicates that, in our simulations, alkalinity addition produces the greatest $p\text{CO}_2$ decline during periods of naturally high CO_2 outgassing, resulting in a seasonal $p\text{CO}_2$ amplitude damping that is relatively more pronounced under low emissions: in the European region, the seasonal amplitude is reduced by 42% (28%) in SSP1-2.6 (SSP3-7.0); in the coastline region, the amplitude is reduced (enhanced) by 18% (11%) in SSP1-2.6 (SSP3-7.0).

This indicates that, in our simulations, alkalinity addition produces the greatest $p\text{CO}_2$ decline during periods of natural CO_2 outgassing. At the European average, this results in a reduction of the seasonal $p\text{CO}_2$ amplitude that is more pronounced under low emissions. Along the coastline, while 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 64: 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. ~~Seasonal amplitude change (OAE — baseline) averaged over 2090-2099 for (a, d) MLD-averaged alkalinity, for (b, e) ocean $p\text{CO}_2$ 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 FOCL, which has a coarser resolution than the ocean component.~~



In the SSP1-2.6 scenario (Fig. 6b), a distinct spatial pattern of pCO₂ seasonal amplitude change driven by OAE is identified. In SSP1-2.6 (fig. 4b), a distinct spatial pattern of pCO₂ seasonal change is identified, with two diverging geographies: at higher latitudes, including off the coasts of Iceland, as well as by the Norwegian and British North-West coastline, the seasonal amplitude slightly increases compared to the control; conversely, at lower latitudes, namely near the continental shelf and by the central-to-southern UK coasts, the seasonal cycle is strongly reduced. In SSP3-7.0 (Fig.

6e), results are amplified in Iceland, in the Southern North Sea, in the UK and Irish coasts. Exceptions are found in the central North Sea and Northern Spain, where strong seasonal amplification is displayed, and off the coasts of Norway, where the ocean pCO₂ seasonal cycle is reduced. ~~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. 4c), 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 amplification is displayed, and by the Norwegian coast, where the ocean pCO₂ seasonal cycle is reduced.~~

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.

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 kg CO₂ m⁻² y⁻¹ in winter and 0.038 kg CO₂ m⁻² y⁻¹ in summer. ~~As for the CO₂ flux, seasonality is driven by temperature in our study area: the system outgasses (takes up) CO₂ in summer (winter), at lowest (highest) chemical solubility, and the largest CO₂ release happens between July and August. Alkalinity addition enhances the CO₂ flux seasonal cycle everywhere and under both warming scenarios, turning the system into a CO₂ sink year round. CO₂ uptake grows more strongly in winter, meaning that alkalisation impacts are largest when ocean uptake is naturally highest, and in SSP3-7.0, meaning that the system becomes more sensitive under higher emissions.~~

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

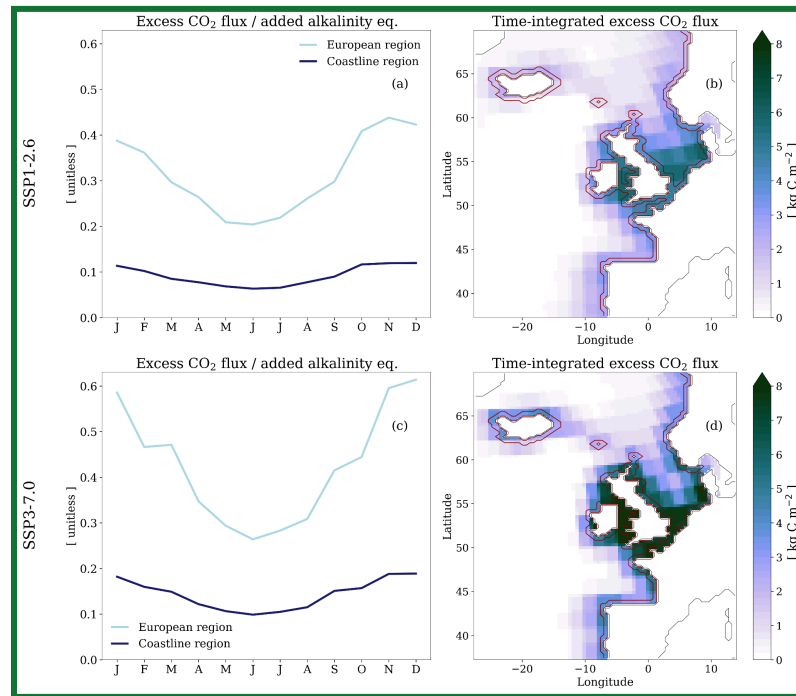
and 0.18 kg CO₂ m⁻² yr⁻¹). This results in a seasonal amplitude enhancement of 51% and of 62% in the low- and high-emission scenario, respectively. In the coastline region, the signal is larger than in the European region: the CO₂ flux seasonal amplitude is 0.329 kg CO₂ m⁻² yr⁻¹, therefore more than 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). ~~For the European average, OAE-induced CO₂ 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). In the coastline of alkalinity addition in the OAE-driven SSP1-2.6 simulation, the CO₂ 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 CO₂ 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 CO₂ 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.~~

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.

Spatially, in SSP1-2.6, OAE amplifies the CO₂ seasonal amplitude along the European coastline, and the signal remains strong until the connection with the open ocean (Fig. 6c). This boundary is set by the 627m isobath, which separates the region with a strong signal from the open ocean, where changes are almost absent. The only exception is found off the Atlantic coasts of Spain, where the signal persists beyond the selected isobath, which may be resulting from ocean circulation dynamics that keep alkalinity at the surface and drive strong winter CO₂ uptake. The seasonal cycle is further amplified under high emissions (Fig. 6f), especially by the coasts of the southern North Sea, the UK and North-West Iceland.

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.



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).

5 Discussion

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).

~~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 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.~~

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. 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. ~~In agreement with Schwinger (2022), OAE works to amplify the CO₂ seasonal flux, prompting greater carbon uptake during winter. This is because OAE effects are larger in the season where higher CO₂ drawdown occurs naturally. Additionally, OAE-induced modifications to ocean pCO₂ are highest in the season~~

~~where the associated seasonal driver reduces the ocean CO₂ sink potential, as alkalised water minimises pCO₂ 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 between semi-enclosed regions and the open ocean, or from differences in the local seasonal driver of the carbon cycle.~~

The seasonal carbon sequestration potential of OAE (Fig. 7) reflects the seasonal trend of the CO₂ flux, whereby uptake increases in winter and it decreases in summer in both the European region and the coastline region, and under both emission scenarios. Importantly, the potential is much larger in the European region than in the coastline region, and under higher emissions than under lower emissions, given that excess CO₂ uptake happens further than the region of alkalinity addition and that it is enhanced in SSP3-7.0 (Fig. 7b, d). This finding is relevant for country-level accountability of OAE deployment, as measurements that are limited to national or regional boundaries may not fully reflect the extent of OAE-driven impacts and therefore underestimate the carbon sequestration potential.~~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 CO₂ 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 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, Palmiéri and Yool (2024) simulated the addition of about 29 Tmol⁻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.

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.

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.

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.

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. However, it is important to highlight that, other than enhancing OAE efficiency, higher atmospheric CO₂ would increase surface temperatures, and thus ocean verification stratification, preventing the entrainment of sequestered carbon to deeper layers (Nagwekar et al., 2024), which an essential aspect to long-term OAE efficiency. ~~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 CO₂ world. Ocean pCO₂ 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 of alkalinity addition amplitude is enhanced, as its sensitivity due to rising temperatures outweighs reduced sensitivity due to alkalinity addition. For the CO₂ 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 CO₂ emissions, than to the background atmospheric CO₂ concentration (Schwinger et al., 2024).¶~~

~~Our results indicate that OAE induced impacts on the seasonal cycle of ocean pCO₂ and the CO₂ 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 CO₂ 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 CO₂ concentrations, which have an amplifying effect on the thermally driven component of ocean pCO₂, lead to an overall expansion of the CO₂ 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. Limitations

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.

Another limitation is that our analysis does not separate the CO₂ flux into its thermal and biological element, therefore missing to discern the influence that each of these elements has in altering the CO₂ seasonal cycle. Given the impacts of temperature and NPP at lower and higher latitude, respectively, in our domain, calculating both terms individually could provide further insight into their seasonal role under OAE deployment. Lastly, this manuscript does not address alkalinised 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.

76 Conclusions

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 alkalinised 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. 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 CO₂ intra-annual variability when continuous coastal OAE is applied. It was found that, in a region of temperature driven seasonality, (a) OAE enhances the CO₂ uptake in winter, when it is naturally strongest, and it reduces ocean pCO₂ in summer, when it is naturally highest; (b) the sensitivity of the seasonal carbon cycle increases under higher emissions, enhancing the CO₂ flux seasonal amplification and contrasting the pCO₂ 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 CO₂ 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 CO₂ flux into its thermal and biological element, therefore missing to discern the influence that each has in altering the CO₂ 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.

8 Author contribution

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..

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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109 Data availability

The datasets used in this manuscript are available at this Zenodo link (https://zenodo.org/records/13935197?token=eyJhbGciOiJIUzUxMiJ9.eyJpZCI6Ijg2ZWViNjU4LWMyZDYtNGFmZCo4MzIoLWUxMmE5YTNhMzdhdNyIsImRhdGEiOnt9LCJyYW5kb2oiOiIyODIyODFjZmUwZTk2MzJjOTcxNGM2ZWZmZW5kNDYwMyJ9.snS8fH7EYBkEYYLP9xUI_P2V4L4HUKBYEi61fFGDd43WwMskAWQBsnfcfdpBMYii_TpWstwKQbsFSCF2K_F4oQ).

The code underlying this study is openly available at the following GitHub repository: https://github.com/chiaraciscato/2025_ciscato_oae_seasonality.~~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).~~

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