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LETTER

On the emission-path dependency of the efficiency of ocean alkalinity enhancement

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Abstract
Ocean alkalinity enhancement (OAE) deliberately modifies the chemistry of the surface ocean to enhance the uptake of atmospheric CO₂. The chemical efficiency of OAE (the amount of CO₂ sequestered per unit of alkalinity added) depends, among other factors, on the background state of the surface ocean, which will significantly change until the end of this century and beyond. Here, we investigate the consequences of such changes for the long-term efficiency of OAE. We show, using idealized and scenario simulations with an Earth system model, that under doubling (quadrupling) of pre-industrial atmospheric CO₂ concentrations, the simulated mean efficiency of OAE increases by about 18% (29%) from 0.76 to 0.90 (0.98). We find that only half of this effect can be explained by changes in the sensitivity of CO₂ sequestration to alkalinity addition itself. The remainder is due to the larger portion of anthropogenic emissions taken up by a high-alkalinity ocean. Importantly, both effects are reversed if atmospheric CO₂ concentrations were to decline due to large-scale deployment of land-based (or alternative ocean-based) carbon dioxide removal (CDR) methods. By considering an overshoot pathway that relies on large amounts of land-based CDR, we demonstrate that OAE efficiency indeed shows a strong decline after atmospheric CO₂ concentrations have peaked. Our results suggest that the assumption of a constant, present-day chemical efficiency of OAE in integrated assessment modeling and carbon credit assignments could lead to economically inefficient OAE implementation pathways.

1. Introduction

Ocean alkalinity enhancement (OAE) has been proposed as a carbon dioxide removal (CDR) technique that would increase the oceans’ capacity to store carbon, thereby taking up CO₂ from the atmosphere (Kheshgi 1995; see Renforth and Henderson 2017 for a review). In contrast to many other gases, CO₂ does not only dissolve in seawater, but it also acts as a weak acid that reacts with water to form free protons (H⁺) as well as bicarbonate (HCO₃⁻) and carbonate (CO₃²⁻) ions. Since atmospheric CO₂ equilibrates solely with the dissolved aqueous CO₂, and not with bicarbonate or carbonate, the ocean holds much more carbon than predicted by the solubility of CO₂. The partitioning of the oceanic pool of dissolved inorganic carbon (DIC) into its constituents (dissolved CO₂, bicarbonate, and carbonate) is governed by the total alkalinity (TA) and the pH of seawater, where TA is defined as the capacity of seawater to neutralize an acid (see, for example, Dickson and Goyet 1994, Wolf-Gladrow et al 2007). An increase in TA shifts the equilibrium of the seawater CO₂ system towards more bicarbonate and carbonate ions, decreases the concentration of dissolved CO₂, and consequently leads to an uptake of CO₂ from the atmosphere. Due to the oceans’ large size, small relative changes in TA could sequester a large proportion of anthropogenic carbon, such that OAE is seen as a CDR technique with high theoretical potential (Kheshgi 1995, Harvey 2008, Ilyina et al 2013, Köhler et al 2013).

The chemical efficiency (η) of OAE has been defined as the carbon sequestration per mole of TA added, η = ∆DIC/∆TA (Renforth and Henderson 2017).
and is a key indicator for assessing OAE as a mitigation option (Oschlies et al 2017), since it affects the economic efficiency (cost per ton of CO$_2$ sequestered) and also monitoring-reporting-verification (MRV) requirements and carbon credit assignment. Many previous modeling studies have investigated large-scale OAE and its efficiency in long-term IPCC emission scenarios up to 2100 and beyond (Harvey 2008, Ilyina et al 2013, Köhler et al 2013, González and Ilyina 2016, Hauck et al 2016, Lenton et al 2018, Köhler 2020). However, despite the seemingly simple definition of $\eta$, there are important differences between studies in how the efficiency of OAE is defined and calculated, making estimates of $\eta$ difficult to compare. It is well known that $\eta$ depends on the chemical state of the surface ocean (e.g. Middelburg et al 2020, Hinrichs et al 2023), which is projected to change due to the anthropogenic CO$_2$ disturbance during the course of this century and beyond. Yet, the consequences of this dependency for long-term deployment scenarios of OAE have never been systematically explored. Many of the studies cited above, have investigated OAE under scenarios of very high future emissions, biasing available estimates of overall OAE efficiency towards high CO$_2$ futures. However, if OAE is deployed to achieve the Paris Agreement temperature targets, strong CO$_2$ emission reductions are required, and plausible long-term emission pathways will show declining and net-negative CO$_2$ emissions. A recent study by Jürchott et al (2023) showed that the efficiency of artificial upwelling critically depends on the assumed emission pathway.

The goal of this study is to provide a sound definition of different efficiency measures, and to systematically explore the effects of the long-term background scenario on the simulated efficiency of OAE. We use idealized Earth system model (ESM) simulations, to attribute changes in $\eta$ to the invasion of anthropogenic CO$_2$ into the surface ocean and to climate change. We then use ESM simulations of the SSP5-3.4 pathway of the Coupled Model Intercomparison Project Phase 6 (CMIP6; Eyring et al 2016) ScenarioMIP (O’Neill et al 2016) to show that our finding from the idealized simulations are indeed relevant for more realistic scenarios.

2. Methods

2.1. Efficiency of OAE

The (chemical) efficiency of OAE is defined as $\eta = \Delta$DIC/$\Delta$TA. In a laboratory this efficiency could be measured by adding TA to a seawater sample and waiting until a new equilibrium with the CO$_2$ in ambient air has been established. Alternatively, since we know the governing equations and reaction rate constants of the sea-water CO$_2$ system, we can express this efficiency following Tyka et al (2022) as

$$\eta = \frac{\partial$DIC}{\partial TA} = \frac{\partial$CO_2}{\partial TA} \div \frac{\partial$CO_2}{\partial$DIC} \approx \frac{1}{3 - 2$DIC/$TA}, \tag{1}$$

where, for the right-hand side approximation, we have assumed DIC $\approx$ [HCO$_3^-\]$ + [CO$_3^{2-}\]$ and TA $\approx$ [HCO$_3^-\]$ + 2$[CO_3^{2-}\]$. We use the subscript $T$ (for ‘theoretical’) to indicate that this is not the efficiency that can be expected in real-world deployment of OAE, because equation (1) indicates that a water parcel attains full equilibrium with the atmosphere. However, if alkalinity is added to the ocean surface, some part of it is mixed downward before an equilibrium with the atmosphere can be reached. A considerable part of CO$_2$ sequestration might therefore occur with a time lag of years to decades and outside the areas where TA has been added (e.g. He and Tyka 2023). Some of the added TA might be lost on even longer timescales if transported into the deep ocean. Therefore, if we estimate the efficiency of OAE using model simulations, deviations from the theoretical efficiency must be expected.

Furthermore, the efficiency of large-scale CDR interventions is influenced by Earth system feedbacks such as a reduced CO$_2$ uptake by natural sinks due to the decreased atmospheric CO$_2$ content (Keller et al 2014, 2018a). Such carbon-cycle feedback effects are not specific to a certain CDR method, and they depend on the scale of CDR (small-scale deployment will not significantly modify carbon-cycle feedbacks). Here, we distinguish the Earth system efficiency ($\eta_{ES}$) and the capture efficiency ($\eta_C$), the former including the effect of carbon-cycle feedbacks. These efficiencies can be derived from model simulations by

$$\eta_i = (F_{OAE} - F) / \Delta$TA, with $i = C$ or ES. \tag{2}$$

Here, $F_{OAE}$ and $F$ are the globally integrated CO$_2$ fluxes in a simulation with and without OAE, respectively. Whether the efficiency resulting from equation (2) is the Earth system efficiency $\eta_{ES}$ or the capture efficiency $\eta_C$ depends on the simulation design. If atmospheric CO$_2$ is prescribed (as in our idealized model simulations, see section 2.2), there are no carbon-cycle feedbacks that could act via changes in atmospheric CO$_2$ concentration and the carbon uptake by OAE is the only process that alters the carbon fluxes. Therefore, if equation (2) is applied to a pair of concentration-driven simulations, it results in the capture efficiency $\eta_C$. If simulations are driven by CO$_2$ emission (as our SSP5-3.4 scenario, see section 2.3), atmospheric CO$_2$ concentration will be lower in the simulation with large-scale OAE, such that carbon fluxes are not only influenced by the OAE deployment but are decreased by carbon-cycle feedbacks. In this case, application of equation (2) will result in $\eta_{ES}$ which is lower than $\eta_C$. To derive the capture efficiency $\eta_C$ from emission-driven simulations, it is
Table 1. Idealized simulations with and without OAE deployment used in this study to derive the OAE efficiencies indicated in the last table row. The prescribed rate of increase of atmospheric CO$_2$ (0.5% or 1% per year) is specified in the simulation names. The subscripts in the simulation names with OAE deployment indicate the rate of TA addition (0.14 or 0.56 Pmol TA per year). All simulations are freely available through the Earth System Grid Federation (ESGF) or the Norwegian Research Data Archive under the DOIs given in parenthesis following the simulation name.

<table>
<thead>
<tr>
<th>Model configuration for idealized simulations (CO$_2$ prescribed)</th>
<th>Standard</th>
<th>Radiative forcing fixed at pre-industrial level</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>No OAE</td>
<td>full-1% (10.22033/ESGF/CMIP6.7802)</td>
<td>no-clim-1% (10.22033/ESGF/CMIP6.13724)</td>
<td>Control (10.22033/ESGF/CMIP6.8217)</td>
</tr>
<tr>
<td></td>
<td>full-0.5% (10.11582/2024.00072)</td>
<td>no-clim-0.5% (10.11582/2024.00069)</td>
<td></td>
</tr>
<tr>
<td>With OAE</td>
<td>full-1%-OAE$_{0.14}$ (10.11582/2024.00068)</td>
<td>no-clim-1%-OAE$_{0.14}$ (10.11582/2024.00085)</td>
<td>control-OAE$_{0.14}$ (10.11582/2024.00074)</td>
</tr>
<tr>
<td></td>
<td>full-1%-OAE$_{0.56}$ (10.11582/2024.00073)</td>
<td>no-clim-1%-OAE$_{0.56}$ (10.11582/2024.00084)</td>
<td>control-OAE$_{0.56}$ (10.11582/2024.00075)</td>
</tr>
<tr>
<td></td>
<td>full-0.5%-OAE$_{0.14}$ (10.11582/2024.00070)</td>
<td>no-clim-0.5%-OAE$_{0.14}$ (10.11582/2024.00071)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>full-0.5%-OAE$_{0.56}$ (10.11582/2024.00072)</td>
<td>no-clim-0.5%-OAE$_{0.56}$ (10.11582/2024.00073)</td>
<td></td>
</tr>
</tbody>
</table>

Derived efficiencies

- Transient OAE capture efficiency $\eta_T$
- Transient OAE capture efficiency $\eta_T$ without climate change effects
- Steady state OAE capture efficiency $\eta_C$

necessary to conduct an additional model simulation (see section 2.3).

2.2. Idealized model simulations

Our simulation design (table 1) builds on pairs of idealized simulations with the Norwegian ESM NorESM2-LM (Selander et al 2020, Tjiputra et al 2020). Each pair consists of a simulation with and without OAE and we derive OAE efficiencies according to equation (2). In simulations with transient CO$_2$ forcing, the atmospheric CO$_2$ concentration is prescribed and rises continuously at a rate of 1% (0.5%) per year until quadrupling (doubling). No other forcings than atmospheric CO$_2$ concentration are varied. In addition to a ‘full’ model configuration, we also run a ‘no-clim’ configuration, where the radiative forcing (i.e. the CO$_2$ concentration in the radiation code) is kept constant at pre-industrial level. In these pairs of simulations, there is no climate change signal such that we can investigate changes in OAE efficiency due to rising atmospheric CO$_2$ without the effects of climate change. A pair of pre-industrial control simulations (‘control’, simulations with fixed pre-industrial CO$_2$ concentration) with and without OAE is used to determine the steady state OAE efficiency.

We have simulated an idealized OAE deployment at two different rates of TA addition, following the protocol of the CDR Model Intercomparison project (CDRMIP; Keller et al 2018b). This idealized deployment does not correspond directly to any of the OAE methods that have been proposed, which differ in the feedstock used, the pre-processing of materials, the distribution and delivery of materials to the ocean, and the reaction pathways that increase TA (Renforth and Henderson 2017). We also do not consider equilibrated TA addition, where an alkaline solution is equilibrated with atmospheric CO$_2$ before it is added to the ocean (Rau and Caldeira 1999, Hartmann et al 2023). Common to all methods is that they eventually would enhance the TA of the ocean, which is the only process that we model, and thereby increase the oceanic carbon pool and decrease the atmospheric CO$_2$ pool by a corresponding amount. The results presented in this study are not particularly sensitive to the TA addition method, although the difference between $\eta_T$ and $\eta_C$ vanishes for perfectly equilibrated TA addition. Some of the proposed methods would also add nutrients (silicate, iron) to the ocean, which can modify the oceanic carbon uptake via alterations of biological activity (e.g. Hauck et al 2016). In this study we ignore such additional effects and consider only carbon uptake due to changes in surface ocean TA. In our idealized set-up, alkalinity is added homogeneously to the surface ocean between 70°S by increasing the model variable TA at a rate of 0.14 Pmol TA yr$^{-1}$ and 0.56 Pmol TA yr$^{-1}$. Note that these rates are not based on considerations of technical or socio-economic feasibility.

2.3. Scenario simulations

To investigate the emission-path dependence of OAE efficiency in a plausible emission scenario, we use NorESM2-LM simulations of the SSP5-3.4 scenario (table 2). This is an overshoot pathway that assumes unmitigated high CO$_2$ emissions until 2040 and aggressive mitigation thereafter, including large-scale deployment of land-based CDR (O’Neill et al 2016). In contrast to the idealized simulations, these scenario simulations are run in CO$_2$ emission-driven mode, such that the atmospheric CO$_2$ concentration evolves according to emissions into the atmosphere and CO$_2$ exchanges with the ocean and terrestrial biosphere.
In the simulations full-1%-OAE, no-clim-1%-OAE, and control-OAE with idealized deployment of OAE, global average surface TA increases by about 100 µmol l\(^{-1}\) by the end of the simulation for a rate of 0.14 Pmol TA yr\(^{-1}\) and by about 400 µmol l\(^{-1}\) for the four-fold addition rate (figure 1(c)). The addition of alkalinity is slightly more effective in increasing the surface concentration of TA in the full simulations, due to increased stratification as mentioned above. The global average surface DIC concentration is not only influenced by the addition of TA and subsequent CO\(_2\) uptake, but also by rising atmospheric CO\(_2\) concentrations in the full (figure 1(d)) and no-clim (not shown) simulations.

### 3.1. Simulated steady state efficiency of OAE

The global average capture efficiency \(\eta_C\) in the control simulations with prescribed constant pre-industrial CO\(_2\) concentration and deployment of OAE is initially as low as 0.2 (figure 2(a)). After about 30–50 years of OAE deployment, \(\eta_C\) reaches a plateau where it slightly increases towards its final value of around 0.76 (average over the last 30 years of the simulation). This behavior can be explained by the timescales of equilibration, consistent with the results of He and Tyka (2023). These authors show that upon addition of TA to the ocean surface, large parts of the excess TA are diluted and mixed downward before equilibration with ambient atmospheric pCO\(_2\), and that the time scale to full equilibration is several years to decades depending on location. In our idealized TA addition scheme, we continuously add alkalinity to the surface ocean, such that at any time \(t\), we see the effects of TA addition at all previous times from \(t_0\) up to \(t\), where \(t_0\) is the start of the simulation. After 30–50 years, a quasi-steady state is reached because the timespan since \(t_0\) is long enough to cover the majority of equilibration timescales at all locations. After this timespan, we expect \(\eta_C\) to roughly equal \(\eta_T\), the fully equilibrated theoretical efficiency (see section 3.3).

There is very little difference between the lower and higher rate of TA addition (figure 2(a)), except for the much larger variability of \(\eta_T\) at the lower rate. This is because \(\eta_C\) is calculated from the air-sea CO\(_2\) flux difference between two simulations (with and without OAE, equation (2)), which are not in phase
Figure 1. Global average time-series from the idealized simulations (table 1). Time series are shown for (a) atmospheric CO$_2$ concentration, (b) global mean surface temperature anomaly, (c) global average surface TA concentration, (d) global average surface DIC concentration. Line colors indicate the full (purple), the no-clim (green), and the control (blue) simulations. Dotted lines in panels a and b show results for the 0.5%–CO$_2$ simulations. Panel c and d show results for simulations without OAE (thin solid lines), OAE of 0.14 Pmol TA yr$^{-1}$ (thick solid lines), and OAE of 0.56 Pmol TA yr$^{-1}$ (thick dashed lines). Results from the 0.5%–CO$_2$ simulations are omitted from panel c and d for clarity.

Figure 2. Simulated capture efficiency of OAE ($\eta_C$) in the idealized NorESM2-LM simulations: (a) $\eta_C$ for the full 1%–CO$_2$ (thick lines) and control simulations (thin lines) with two different rates of OAE (blue lines 0.14 Pmol TA yr$^{-1}$, red lines 0.56 Pmol TA yr$^{-1}$); (b) $\eta_C$ for the full and no-clim 1%–CO$_2$ and 0.5%–CO$_2$ simulations (TA addition of 0.56 Pmol yr$^{-1}$); (c) $\eta_C$ for the 1%–CO$_2$ and 0.5%–CO$_2$ simulations (TA addition of 0.56 Pmol yr$^{-1}$) plotted versus atmospheric CO$_2$ concentration.

with respect to modes of internal variability. For the lower rate of TA addition, the internal variability has a larger impact relative to the signal of OAE induced CO$_2$ fluxes, but the longer-term averages are very similar (the difference being less than 2.5% when averaged over the last 30 years of the simulations, table 3).
3.2. Simulated efficiency of OAE in idealized transient simulations

In the full-1%–OAE simulations (figure 2(a)), \( \eta_C \) is significantly larger than in the control-OAE simulations and shows an increasing trend also after the first 30–50 simulation years. Towards the end of the simulations (average over the last 30 years) we find \( \eta_C \approx 0.98 \) for the full-1%–OAE simulations compared to \( \eta_C \approx 0.76 \) for the control-OAE simulations. As seen above for the control-OAE simulations, the carbon uptake of the full-1%–OAE simulations scales almost perfectly with the rate of TA addition, resulting in very similar values of \( \eta_C \) for the two different rates of TA addition with a difference of less than 2.5%.

What are the reasons for the differences in OAE capture efficiencies between the transient and control simulations? As we have seen above (figure 1(c)), a more stratified ocean makes OAE deployment potentially more efficient by retaining more of the added alkalinity close to the ocean surface. On the other hand, a high-alkalinity ocean generally loses more \( \text{CO}_2 \) when sea-water temperature increases (see supplementary information and figure S1). By comparing the efficiencies in the full and no-clim simulations (figure 2(b) and table 3), we find that the net effect of climate change is a reduction of OAE efficiency, but this effect remains very small. When averaged over the last 30 years of the simulations, climate change reduces the efficiency of OAE by less than 1% for the 1%–\( \text{CO}_2 \) simulations, and by less than 1% for the 0.5%–\( \text{CO}_2 \) simulations. Therefore, climate change effects cannot explain the larger efficiencies in the transient compared to the control simulations. Instead, these differences must be due to chemical effects (changing sensitivities of the \( \text{CO}_2 \)-system), which we will investigate further in the next section.

3.3. Theoretical versus simulated capture efficiency

The theoretical efficiency of OAE (\( \eta_T \)) is calculated from surface DIC and TA according to equation (1). Figure 3 shows a close agreement between theoretical efficiencies for the low and high rates of TA addition with differences of less than 2.5% (slightly larger for the low rate, table 3) similar to what we have found for \( \eta_C \). There is little interannual variability for \( \eta_T \) since this quantity is calculated from DIC and TA fields of the same simulation, which strongly covary.

For the control simulations (figure 3(a)), there is also a close agreement between \( \eta_C \) and \( \eta_T \), after the initial increase of \( \eta_C \), with values around 0.76 (average over the last 30 years of the simulations). This supports the hypothesis that in our simulations with continuous TA addition, \( \eta_C \) approaches \( \eta_T \) once the simulation covers a long enough time interval that the major equilibration timescales for all regions are represented.

For the full-1%–OAE simulations (figure 3(b)), there is a clear difference between \( \eta_C \) and \( \eta_T \), which can be explained by the changing sensitivities of the
carbonate chemistry system with increasing DIC concentration. Both, $\eta_C$ and $\eta_T$ show an increasing trend over time consistent with a larger carbon sequestration per mol TA at high DIC values (figure S1). However, while $\eta_T$ increases linearly to values of 0.88–0.90, the increase for $\eta_C$ is much larger, reaching values of 0.98–0.99 (average over the last 30 years of the full simulations, table 3). This effect can be explained by the fact that the same atmosphere-ocean $pCO_2$ disequilibrium leads to a larger air-sea $CO_2$ flux under high alkalinity as shown in the supplementary and in figure S1. The theoretical efficiency $\eta_T$ does not account for the $CO_2$ partial pressure disequilibrium between atmosphere and ocean in the transient simulations. Therefore, the increase in $\eta_T$ indicates only the increased CO$_2$ sequestration due to an increased sensitivity to TA addition at high DIC concentrations (figure S1), and we use $\eta_T$ to estimate the contribution of this effect. The increase from the preindustrial $\eta_C \approx \eta_T = 0.76$ to $\eta_T = 0.88$ and $\eta_C = 0.98$ indicates that the effect of the transient disequilibrium is 43% of the total efficiency increase in the full-1%-OAE simulations.

For the full-0.5%-OAE simulation (figure 3(c)), $\eta_T$ and $\eta_C$ increase at a significantly slower rate with values of 0.82 and 0.90, respectively, towards the end of the full-0.5%-OAE simulation. Interestingly, this indicates that the relative effect of the transient disequilibrium is larger (relative to the change in direct efficiency of TA addition), namely 57% of the total effect. We note that we have used the approximation for $\eta_T$ made in equation (1) and that numbers given here for the effect of the transient disequilibrium will slightly differ for an exact calculation.

### 3.4. OAE efficiency in an overshoot scenario simulation

Atmospheric $CO_2$ concentration in our SSP5-3.4-OAE scenario peaks in 2056, three years earlier than in the standard SSP5-3.4 (figure 4(a)). After the peak it declines in both simulations until about 2155. The land-based negative emissions in SSP5-3.4 are ramped back to zero between 2140 and 2170 (Meinshausen et al 2020), but in our SSP5-3.4-OAE, the deployment of OAE continues until 2220. Therefore, the atmospheric $CO_2$ concentration slightly increases again after about 2160 in the standard scenario, because carbon back-flux from the ocean and the terrestrial biosphere (figures 4(b) and (c)) is not countered by negative emissions, an effect that is reduced in SSP5-3.4-OAE. The air-sea $CO_2$ fluxes in the SSP5-3.4-B2 simulation are always smaller (less ocean $CO_2$ uptake and increased $CO_2$ back-flux to the atmosphere) than in the standard scenario,
4. Conclusions

Model simulations will be needed to assess deployment of OAE and to implement accounting schemes for the CDR that is achieved through OAE. We have shown that the chemical efficiency of OAE (mol of CO₂ removed per mol of TA added) depends critically on the background emission scenario, under which a long-term deployment of OAE is assumed. We have described two main mechanisms that explain an increase of the efficiency of OAE with higher atmospheric CO₂ concentrations. First, more CO₂ is taken up per addition of 1 unit of TA when atmospheric CO₂ increases. Second, a high-alkalinity ocean takes up a larger fraction of anthropogenic emissions. Importantly, both of these effects are reversed under decreasing atmospheric CO₂ as we have shown for a scenario simulation with large scale deployment of both OAE and land-based CDR. The effects of climate change (e.g. warming, stratification, and circulation changes) on the efficiency of OAE are only of secondary importance as we have shown using idealized model simulations where the climate change signal is suppressed.

The continuous and near-global coverage OAE deployment considered in this study is highly idealized. In a hypothetical real-world deployment, OAE would happen much more localized and intermittent (e.g. Bach et al 2023, He and Tyka 2023). However, our main findings are based on well-understood carbon chemistry, and we believe that our results are relatively robust and apply to more realistic deployment scenarios, at least qualitatively. Future work should further investigate the long-term scenario dependence of OAE efficiency in local and regional realistic deployment scenarios.

Given the scenario-dependent chemical efficiency of OAE, any accounting scheme that uses TA addition information as a basis for allocating carbon offset credits should also apply scenario-specific conversion rates to calculate offset credits from the amount of alkaline material added to the ocean. The SSP5-3.4 OAE simulations show that assuming a constant conversion rate of about 0.8 (as suggested by ηₙ at the start of the SSP5-3.4 OAE scenario) throughout the period to 2100 would not properly incentivize the optimal use of OAE. Scenario-specific conversion rates would instead increase the incentives for OAE deployment when it is most needed around the maximum of atmospheric CO₂ concentrations, while also supporting its phase-down or even phase-out under declining atmospheric CO₂ conditions. The simulations also show that the Earth system OAE efficiency (η_ES) is significantly lower than the OAE capture efficiency (η_C). Both pieces of information are needed, the former for cost-benefit climate policy considerations and the latter for cost-effectiveness climate policy considerations. Obviously, deciding about optimal climate polices and CDR deployment in a cost-benefit sense requires to consider the Earth system perspective including all feedbacks as reflected in η_ES. However, given a climate target and assuming that a corresponding climate policy is in place with instruments like emissions trading implemented, the target is to be achieved cost-efficiently, which requires that different CDR methods can be compared in terms of their cost per amount of carbon captured. Accordingly, in such a cost-effectiveness framework, the capture efficiency η_C would be relevant for determining the amount of carbon offset credits. Note that currently, there is neither an agreed-on method for MRV and carbon offset accounting for OAE, nor is there a framework that would integrate OAE and marine CDR in general into climate policies. In this context, our study highlights the importance of considering variable scenario-dependent long-term efficiencies for OAE and the critical role of model simulations in addressing this issue.

Data availability statement

The NorESM2-LM model output used in this study is freely available through the Earth System Grid Federation (ESGF) and the Norwegian Research Data Archive. DOIs for each simulation are given in
tables 1 and 2. NorESM2 including the newly added OAE source code is freely available on github https://github.com/NorESMhub/NorESM/archive/refs/tags/release-noresm2.0.7.tar.gz.

All data that support the findings of this study are included within the article (and any supplementary files).

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