Model-based assessment of carbon dioxide removal effect through different ocean alkalinity enhancement technologies

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Abstract: This study investigates the long-term impacts of Ocean Alkalinity Enhancement (OAE) on global carbon cycling and climate systems under the high-emission SSP5-8.5 scenario using the UVic Earth System Climate Model (UVic_ESCM). By comparing three OAE technologies, namely, Hydroxide Ocean Liming (HOL), Limestone CO_2 Leaching (LCL), and Olivine Ocean Dumping (OOD), key findings reveal distinct performance patterns. HOL achieves the most pronounced atmospheric CO_2 reduction, lowering concentrations by -484.1 ppm by 2099, followed by OOD (-449 ppm), while LCL exhibits weaker net mitigation (-242.3 ppm) due to carbon release from mineral dissolution. In terms of oceanic carbon sequestration, LCL yields the highest cumulative increase owing to additional dissolved inorganic carbon (DIC) from carbonate dissolution. The study also identifies terrestrial carbon loss (-126 Gt C for HOL) and oceanic carbon re-release, underscoring the need to balance sequestration efficiency, dynamic feedbacks, and ecological risks. OAE markedly elevates seawater pH and aragonite saturation states ($\Delta\Omega$ up to 50), though LCL shows minimal pH enhancement due to DIC buffering. These results highlight OAE's potential to enhance marine carbon sinks and mitigate acidification, yet practical implementation requires optimizing mineral dissolution kinetics and minimizing supply-chain carbon emissions. The findings emphasize the importance of difference OAE technologies' effects on carbon removal.

1 Introduction

1.1 Climate change

Climate change is a global problem caused by the increase of greenhouse gases in the atmosphere [1-2]. Observations show that by 2024, the concentration of CO_2 in the atmosphere has reached 422 ppm (parts per million), which is approximately 47% higher than that before the Industrial Revolution. Ongoing climate negotiations have recognized that there is a large gap between the current trajectory of global greenhouse gas emissions and the goal of holding the global average temperature increase below 2 °C or 1.5 °C above pre-industrial levels[1]. In order to achieve this goal, it is not enough to reduce the emission of CO_2, and some measures are still needed to limit and reduce the amount of CO_2 in the atmosphere[3], that is, carbon dioxide removal (CDR). The Intergovernmental Panel on Climate Change (IPCC) reports that if the global temperature rises by more than 1.5 degrees Celsius, the temperature rise can be gradually reduced by achieving and maintaining a net negative global CO_2 emission. This requires additional deployment of CDR technology[4]. Some form of CDR may be needed to achieve climate goals, according to the American Academy report, to reduce emissions by about 10 Gt CO_2 per year by mid-century and 20 Gt CO_2 per year by the end of the century[5].

1.2 Ocean-based carbon dioxide removal

Ocean covers 70% of the Earth's surface, provides most of the global natural carbon sequestration capacity, and it is possible to improve this capacity by implementing an ocean-based CDR approach. The ocean has a great potential for absorbing and long-term sequestration of anthropogenic CO_2 for three reasons. First, the ocean is a huge natural reservoir of CO_2, and its inorganic carbon storage is about 50 times that of the pre-industrial atmosphere. Second, the ocean has removed a large part of the CO_2 emitted by human beings. Last reason is many physical, geochemical and biological processes are known to affect air-sea CO_2 exchange and ocean carbon storage.

From the beginning of the 1960s to the end of the 2010s, the ocean absorbed 25% ± 2% of the total anthropogenic CO_2 emissions, and the rate of CO_2 absorption by the ocean more than tripled during this period, averaging -2.7 ± 0.3 Pg C · year^{-1} between 1990 and 2019[6], Moreover, the ocean still has a large carbon absorption potential for a long time[3]. Given the increasing reliance on carbon removal technologies for scenarios to meet climate goals and the scale of carbon sequestration that may be required, it is important to

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explore and understand all possible possibilities for enhancing ocean carbon sinks.

1.3 Ocean alkalinity enhancement

Ocean Alkalinity Enhancement (OAE) is an ocean-based CDR technology proposed in 1995[7]. OAE artificially increases ocean alkalinity by adding alkaline minerals or their dissolution products to the ocean to increasing the ocean's ability to absorb CO_2 on a certain time scale[5]. Adding alkalinity to seawater converts the aqueous CO_2 in ocean to inorganic carbon (DIC), which reduces the partial pressure of CO_2 (pCO_2) between the ocean-atmosphere system, resulting in an uptake of CO_2 by the ocean. OAE can not only enhance ocean carbon absorption, but also reverse ocean acidification and increase ocean buffer capacity by changing the chemical properties of seawater. Therefore, OAE is considered as a feasible marine CDR technology[5].

Current research on OAE primarily focuses on four technologies. The first technology, inspired by natural mineral weathering, involves using lime (CaO or $Ca(OH)_2$) derived from limestone calcination to enhance ocean alkalinity. In this research, this technology is designated as Hydroxide Ocean Liming (HOL). Compared to other alkaline minerals, lime dissolves readily in surface seawater and reacts with CO_2 as follows:

$$CaO + 2CO_2 + 2H_2O = Ca(HCO_3)_2 \quad (1)$$

A second strategy, employs carbonate minerals (e.g., $CaCO_3$) exposed to CO_2-rich gas streams and seawater to increase alkalinity. We designate this technology as Limestone CO_2 Leaching (LCL). High CO_2 partial pressure enables spontaneous carbonate dissolution in seawater, producing alkaline effluents. While the stored carbon form matches that of lime, the reaction pathway differs:

$$CaCO_3 + H_2O + CO_2 = Ca(HCO_3)_2 \quad (2)$$

The third technology involves the direct deployment of ground olivine into the ocean to enhance alkalinity, which we designate as Olivine Ocean Dumping (OOD). The reaction of olivine with CO_2 in seawater is as follows:

$$Mg_2SiO_4 + 4CO_2 + 4H_2O = 2Mg(HCO_3)_2 + H_4SiO_4 \quad (3)$$

2 Method

2.1 Earth system model description

In this study, we utilize version 2.9 of the University of Victoria Earth System Climate Model (UVic_ESCM) for numerical simulations. It is a medium - complexity model which has three dynamically coupled components [8]. Uvic_ECM divides the global into 100 grids and the ocean part has 19 vertical levels, with thicknesses varying from surface ocean to 6080 m in the deep ocean. The mathematical formulations for ocean - atmosphere gas exchange and seawater carbonate chemistry are based on the Ocean Carbon Cycle Model Intercomparison Project (OCMIP). abiotic protocol. The land model for vegetation and carbon cycle is based on the Hadley Centre Model. The atmospheric energy-moisture balance model interactively calculates heat and water fluxes to the ocean, land, and sea-ice. Wind speed is used to calculate momentum transfer to the ocean and sea - ice models, surface heat and water fluxes, and advective transport of water vapor in the atmosphere. It's determined by adding wind and wind stress anomalies to prescribed monthly climate wind data. This model has been widely used for studying climate and carbon cycle changes caused by CDR technologies like ocean alkalinity enhancement, and it has been well - validated from pre - industrial to present conditions.

2.2 OAE simulation

This study focuses on implementing OAE within the exclusive economic zones of major global economies to assess its impacts on atmospheric CO_2 dynamics and spatiotemporal distributions of oceanic inorganic carbon. The selected EEZs encompass ice-free coastal grid cells between 60°N and 60°S. The background CO_2 emissions data are based on the SSP5-8.5 scenario, with the model running from 2030 to 2099. Alkalinity addition can be categorized into two broad classes based on the mineral products employed. The first assumes minerals such as lime to instantaneously mix and dissolve upon ocean discharge, while the second ac-counts for gradual dissolution of spherical particles influenced by grain size, seawater temperature, and pH, as exemplified by olivine. In this study, HOL and LCL technologies adopt the former parameterization scheme, whereas OOD is modelled using a shrinking-core dissolution framework to capture its time-dependent dissolution dynamics. Alkalinity addition commenced in 2030 under SSP5-8.5. In this OAE setup, a large-scale deployment was simulated, with annual alkalinity inputs uniformly distributed across target marine grids. The alkalinity enhancement rate was set to the anthropogenic CO_2 emissions.

3 Results and discussion

3.1 Carbon removal effects of different OAE technologies

Alkaline mineral addition triggers carbonate chemistry reactions with seawater CO_2, effectively enhancing ocean carbon sink capacity and facilitating the transfer of atmospheric CO_2 into the ocean. Over a 70-year simulation period, all three technologies under the SSP5-8.5 scenario demonstrate atmospheric CO_2 concentration reductions compared to control simulations without OAE. However, their efficiencies exhibit marked heterogeneity across methodologies. Among these, HOL exhibited the most pronounced mitigation effect, decreasing from -0.7 ppm in 2030 to -484.1 ppm by 2099. LCL followed with a reduction from -0.3 to -242.3

ppm, while OOD initially showed no effect in 2030 (0 ppm) but began to take effect from 2031 onward, reaching -449 ppm by 2099. The mitigation rates of all three technologies accelerated over time, with a sharp intensification post 2050. For instance, HOL achieved an annual reduction of ~2.4 ppm between 2030 and 2050, which surged to ~8.5 ppm annually from 2050 to 2099 (Figure 1). This divergence stems from variations in dissolution kinetics, alkalinity release rates, and biogeochemical feedbacks inherent to each deployment strategy. The differential performance under-scores the critical role of mineral-specific dissolution dynamics in modulating both short-term CO_2 drawdown and long-term carbon storage outcomes. Notably, under the OOD technology, the olivine deployed during the simulation period did not fully dissolve. Our simulation results indicate that only approximately 90% of the olivine achieved complete dissolution and carbon sequestration.

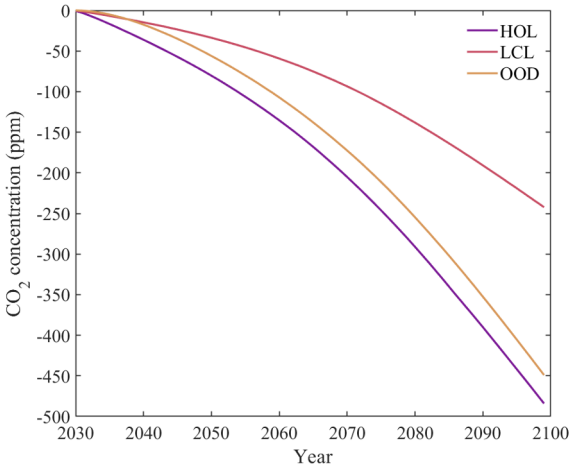

Figure 1. Changes in atmospheric CO_2 concentration caused by three technologies.

3.2 Impact of OAE on global carbon pool

The addition of alkalinity to the ocean boosts its carbon uptake capacity through chemical reactions (Table 1, Figure 2). Among the three technologies, LCL achieves the highest ocean carbon increase (1500 Gt C), followed by HOL (1154 Gt C), with OOD being the lowest (1055 Gt C), reflecting their distinct application features. LCL's chemical principle (Eq.2) shows that it raises ocean alkalinity and adds extra carbon from minerals ($CaCO_3$), leading to higher ocean carbon input than other technologies (Figure 2b). In contrast, OOD's dissolution core model means the added minerals don't fully dissolve over 70 years, resulting in a slightly lower ocean carbon increase compared to the rapidly dissolving HOL (Figure 2c).

After alkalinity addition, the reaction between alkaline minerals and CO_2 in the ocean disrupts the sea-air balance, promoting atmospheric carbon uptake into the ocean via Henry Law. Among the three technologies, HOL achieves the highest atmospheric carbon reduction (-1028 Gt C), followed by OOD (-953.1 Gt C), with LCL being the lowest (-514.5 Gt C). Despite both assuming instant mineral dissolution and CO_2 reaction, LCL and HOL differ in the carbon from minerals, which can be released back to the atmosphere as CO_2 in the ocean's dynamic environment. Figure 2 shows that LCL has a lower ocean carbon uptake rate within the alkalinity addition grid cells than the other technologies. This CO_2 re-release weakens LCL's atmospheric carbon reduction compared to HOL and OOD. Another impact of OAE on the global carbon cycle is the release of land carbon (Table 1). Results show that among the three technologies, HOL has the strongest impact on land carbon (-126 Gt C), while LCL has the weakest (-38 Gt C). This is because reduced atmospheric carbon weakens plant photosynthesis, leading to more land carbon release[9].

Table 1. Changes in the global carbon pool induced by three technologies in 2099.

Technologies	Atmospheric carbon (Gt C)	Oceanic carbon (Gt C)	Land carbon (Gt C)
HOL	-1028	1154	-126
LCL	-514.5	1500	-38
OOD	-953.1	1055	-102

3.3 Impact of OAE on global temperature

The three technologies have all to some extent helped lower global temperatures. HOL and OOD can each reduce global temperatures by up to 4.5°C, while LCL only manages a 1.5°C reduction (Figure 3 d-f). This mirrors the global CO_2 concentration trends. Overall, the results indicate that the Arctic and Antarctic regions experience greater cooling than other areas, with the Northern Hemisphere cooling more significantly than the Southern Hemisphere. There are several key reasons for this:

As CO_2 levels decrease and the greenhouse effect weakens, high - latitude regions, with their year - round low temperatures, become more sensitive to long - wave radiation, causing polar regions to cool faster than mid - and low - latitude regions. In the Arctic, the expansion of sea ice increases solar radiation reflection, further intensifying cooling in some areas. In contrast, the Antarctic's cooling is somewhat buffered by the thermal inertia of its ice sheets. The Northern Hemisphere has a higher proportion of landmass. Land has a lower heat capacity and responds quickly to temperature changes, thus accelerating surface cooling. Ocean currents also play a regulatory role. In the North Atlantic, the Meridional Overturning Circulation strengthens its sinking branch due to high-latitude cooling, reducing northward heat transport. Meanwhile, the Antarctic Circumpolar Current isolates deep water, causing a lag in heat release from the Southern Hemisphere oceans and making temperate oceans in the Northern Hemisphere cool more noticeably.

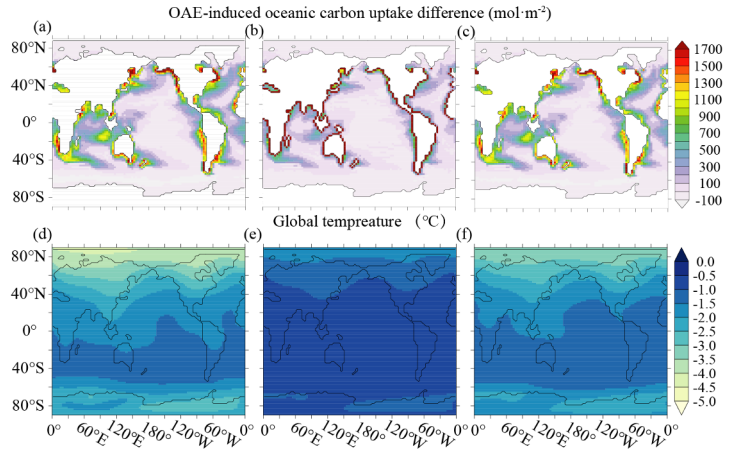

Figure 2. Differences in oceanic carbon uptake and global temperature induced by HOL (a, d), LCL (b, e), and OOD (c, f) relative to the control simulation.

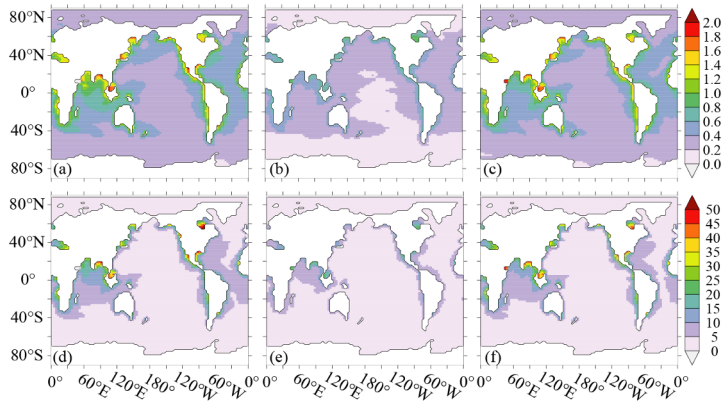

Figure 3. Differences in ocean pH and aragonite saturation state (Ω) in 2099 induced by HOL (a, d), LCL (b, e), and OOD (c, f) relative to the control simulation. Panels a–c depict pH, while Panels d–f show Ω.

3.4 Effects of OAE on ocean chemistry

After using OAE, changes in seawater pH and aragonite saturation state (Ω) occur. OAE significantly raises the pH in the simulated areas, particularly in the alkalinity-addition grid cells and nearby waters. HOL and OOD can increase surface pH by over 2.0 compared to the control group. LCL, which has the least pH impact among the four technologies, raises ocean pH by up to 0.8 less than the other three. This is because the DIC from the added minerals weakens the pH change (Figure 3).

The Ω in seawater, which is crucial for assessing ocean acidification, is closely related to pH. It is defined as the ratio of the product of calcium and carbonate ion concentrations to the apparent solubility product of aragonite[10]. When seawater alkalinity increases, hydrogen ion concentration drops, directly raising pH. The carbonate system then rebalances, increasing carbonate ion concentration. Since Ω depends on this concentration and that of calcium ions, carbonate ions' rise also boosts Ω. In this study, under SSP5-8.5, the three technologies can raise Ω by up to 50 (Figure 3).

This is because seawater is in a dynamic equilibrium after alkalinity addition. In the short term, surface water pH rises and pCO_2 falls, but the CO_2 partial pressure gradient between seawater and the atmosphere drives more atmospheric CO_2 to dissolve in the ocean, significantly increasing DIC. The dissolved CO_2 then generates carbonic acid through hydration, which dissociates into hydrogen ions and bicarbonate ions. This raises hydrogen ion concentration and brings seawater pCO_2 back up towards atmospheric equilibrium. This process demonstrates the dynamic feedback of the marine carbonate system, which re-establishes equilibrium through air-sea exchange and chemical reactions after human intervention.

However, excessive increases in Ω, pH, and carbonate ions beyond current or pre-industrial levels may have unforeseen and potentially harmful biological effects. Additionally, for OOD, using larger - grained olivine would slow down the rise in Ω, pH, and CO_2 sequestration due to slower dissolution. Undissolved olivine particles might also harm benthic ecosystems through mechanical and optical effects.

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4 Conclusion

This study based on the UVic_ESCM model, comprehensively assesses the impacts of ocean alkalinization enhancement (OAE) on the global carbon cycle, climate system, and marine environment under high CO_2 emission scenarios (SSP5-8.5). In our simulation experiments, carbon removal efficiencies vary across OAE technologies, with Hydroxide Ocean Liming (HOL) being the most effective. However, HOL involves a high-emission lime industry, requiring additional carbon emission considerations in practical applications.

OAE significantly increases ocean carbon sinks but triggers complex carbon feedbacks through ocean dynamics. Under SSP5-8.5 scenario, LCL yields the highest ocean carbon increase due to extra DIC from carbonate mineral dissolution, yet causes more CO_2 outgassing. Our results confirm OAE's potential for enhancing carbon sinks and mitigating acidification, but its effectiveness is subject to ocean dynamics, technological choices, and global carbon cycle feedbacks. Key challenges involve carbon leakage reducing net removal benefits and possible land carbon losses offsetting some ocean gains.

Acknowledgments

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