

Response to the Reviewer 1

General Comment

The study quantifies 1) the efficiency of a continuous global application ocean alkalinity enhancement using several metrics, 2) the subsequent response of the global carbon fluxes, and 3) the long-term potential of OAE to mitigate ocean acidification. The authors used an Earth System Model to simulate three atmospheric temperature stabilization scenarios to year 2500. For each scenario, five realizations with and five realizations without OAE were produced in order to quantify the direct response of the system to OAE, and to quantify the impact of climate feedbacks.

Results indicate that OAE efficiency estimated with the metric that accounts for climate feedbacks is much lower than the maximum potential efficiency only based on carbonate chemistry. The authors rightly discuss in which circumstances one metric should be favoured than the other. The study also shows that in centennial timescales, under continuous global deployment of TA, it is the reduction in atmospheric CO₂ the main driver of acidification mitigation, while the impact of OAE itself is less prominent. This is a relevant message given that ocean acidification mitigation is typically presented as a beneficial side-effect of OAE deployment.

The manuscript is mostly clearly written and the messages are relevant and worth publishing. Some comments and suggestions below:

Response:

We thank the reviewer for the positive assessment and the constructive suggestions to further improve the manuscript. Detailed replies to each specific comment follow below.

Specific Comments

1. The authors acknowledge in their caveats section that the CO₂ emissions related to producing the alkaline material need to be taken into account in future studies. I would suggest bringing this caveat earlier in the manuscript (maybe in the setting of the simulations). Should the reader interpret that the production of alkaline material in this idealized framework does not produce further emissions?

Response: We agree and have clarified this earlier in the manuscript. We now state in the method section: "Additional CO₂ emissions due to the OAE intervention, associated with the mining, processing, and transport of alkaline materials or solutions (*Foteinis et al., 2022*) are not included in this study." We additionally added a clarifying sentence in the definition of the net ocean capture efficiency: "Different to how net efficiency is defined here, this term sometimes also refers to the OAE efficiency including life-cycle emissions (*Foteinis et al., 2022; Delval et al., 2025; Katish et al., 2026*)."

2. Please clarify in which way a continuous global alkalinity addition “approximates” discrete OAE pulses. Please elaborate on the broad shared characteristics mentioned in L470-471. With the experiments presented, is it possible to state that the climate and carbon cycle responses will be similar with continuous global vs discrete OAE pulses?

Response: Based on our understanding, we believe that the response of global carbon cycle feedbacks guiding the net ocean capture efficiency, as also shown by *Tyka* (2025), and the ocean acidification response show the same characteristics for individual OAE pulses, and hence also the large-scale climate response. However, we acknowledge, that we can not state this based on our data and since another reviewer raised the same point, we now refrain from making this rather speculative statement. We now just say: “Continuous addition is likely feasible at specific coastal sites, such as industrial water outlets (*Wang et al.*, 2023; *Burt et al.*, 2024) and continuous alkalinity addition may well approximate the alkalinity release from frequent individual pulses necessary for OAE at scale.”

L25: Ongoing mitigation efforts such as?

L25: I agree that emissions reductions remain inadequate but not despite ongoing mitigation efforts, as these two are different activities. Please consider rephrasing.

Response: Thank you for pointing that out. We have rephrased it to: “Ongoing efforts to reduce emissions remain inadequate and global temperatures are now on track to exceed the 1.5 °C threshold of the Paris Agreement in the next decade.”

L105-106: Please clarify the difference between the observed CO₂ emissions for the 1861-2005 period and the observed CO₂ emissions from 2005 to 2020.

Response: We have clarified that historical emissions follow the CMIP5 protocol and are extended with observed emissions for 2006-2020: “After an initial spin-up (*Burger et al.*, 2020), an emission-driven historical simulation was performed over the period 1861 to 2005, which follows fossil fuel and land-use change CO₂ emissions as well as prescribed non-CO₂ radiative forcing agents from the CMIP5 protocol. This simulation was continued for 20 simulation years in which fossil fuel CO₂ emissions followed observed emissions until 2020 and national determined contributions until 2025 (*Friedlingstein et al.*, 2020; *Silvy et al.*, 2024).”

L108: is “current” the right word here? Or maybe “the warming level for the corresponding period”?

Response: We have changed it to: “The pathway is recalculated every five years based on updated estimates of global mean temperature and the remaining CO₂-forcing-equivalent emission budget at the time of the stocktake.”

L114-116: the CO₂ emissions followed for the CDRMIP protocol do not account for any CO₂ produced during the production of TA. If this is correct, please state it here.

Response: That is true, we have added this sentence here: “Additional CO₂ emissions due to the OAE intervention, associated with the mining, processing, and transport of alkaline materials or solutions (*Foteinis et al.*, 2022) are not included in this study.”

L155, Equation 2. the fluxes from which simulation were removed from which other simulation? For the same ensemble? Or from the mean? Please include this clarification. Also, are the differences estimated on a year by year basis?

Response: The used simulations are described below the equation: "The nominator represents the additional CO₂ uptake by the ocean in the 'OAE' simulation relative to the reference simulation 'Ref', both following the same emissions trajectory. F_{ALK} denotes the rate of alkalinity addition of 0.14 Pmol yr⁻¹." We have added the following sentence to further clarify: "Efficiencies are calculated for each ensemble member individually and are based on annual mean carbon fluxes."

L220: But considering the ensemble ranges, the peak is only truly different in the 3 deg OAE scenario compared to the REF.

Response: We have clarified the statement recognizing the ensemble range: "The 31-year mean peak atmospheric CO₂ is lower and earlier with OAE than without on the ensemble average, albeit with overlapping ensemble ranges: at 468 ppm [437-488] in year 2059 [2041-2088] in the 1.5 °C scenario, at 546 ppm [524-560] in year 2085 [2076-2097] in the 2 °C scenario and at 689 ppm [677-708] in year 2167 [2158-2178] in the 3 °C scenario."

L245: "opposite sign" was confusing on a first read, as the global warming pattern is not shown. Please rephrase, if possible.

Response: We clarify: "The regional temperature response to global OAE deployment (Fig. C2a-c) closely mirrors the spatial pattern of greenhouse gas-induced warming (c.f. Fig. 4.19 in *Lee et al.* (2021), but with the opposite sign."

L272 and 273: revise the plurals, change "signals" to "signal" and "oceans" to "ocean"

Response: Thanks for the pointer. Changed.

L292 and Figure 7: In Figure 7 the decline in net ocean capture efficiency seems linear and is hard to note the "before and after the peak in atm CO₂". Does it make sense to indicate with a vertical line the timing of the peak atm CO₂ for each scenario? Also because this pre-peak and after peak measure is used in the following paragraphs.

Response: We have added a vertical line indicating the ensemble average year of peak atmospheric CO₂.

L301-303: stronger stratification would be expected in a warming scenario, and therefore shallower mixed layer depths. How is it that the mixed layer depth increases 10 times by 2500?

Response: This is not the depth of the general mixed layer, but a proxy that estimates the vertical distribution of the alkalinity plume over time. Alkalinity is added at the surface and gets vertically distributed by ocean currents and mixing over time. This "effective mixed layer depth" refers to the alkalinity plume and not the normal mixed layer at the ocean surface. We have clarified the sentence explaining this effective mixed-layer depth: "We use the effective mixed layer depth for

OAE from *Zhou et al.* (2024), characterizing the ocean volume under influence of alkalinity addition. Note that this is not the depth of the commonly used wind-driven mixed layer.”

L309: Please include a noun after “This”, maybe “efflux”? Same comment for L316.
L317: both processes? Would not calcification be considered one process?

Response: We have added ”efflux” in L309 and adjusted the latter sentences for clarification: ”Calcification reduces DIC, allowing for further ocean carbon uptake and increasing efficiency, but also removes alkalinity and thereby decreases efficiency. Overall, calcification leads to a net reduction in efficiency since calcification removes twice as much alkalinity as DIC, leaving a net increase in $p\text{CO}_2$.”

L339: but also the CO₂-driven was extended? It appears so, as the gross efficiency is shown. Please state so.

Response: Yes, it was. We have adjusted the sentence and moved it to the methods section, following reviewer 3: ”To investigate the effect of OAE termination on both the efficiencies and the ocean acidification response, we extended one ensemble member of the 2°C OAE simulations to the year 3000, but terminating OAE in 2500, and extended both reference simulations as well.”

L369: “arising”? Or you could also just remove arise altogether.

Response: We have removed ”arise”. Thank you.

L411: an end of sentence period is missing after the references.

Response: Done.

Figure 1. If the reference simulations stabilize air temperature without OAE, what do they do?

Response: We have clarified the description to ”The reference simulations (Ref) stabilize global surface air temperature at 1.5 °C, 2 °C and 3 °C following the adaptive emission reduction approach and have no ocean alkalinity enhancement (OAE). Corresponding OAE simulations follow the same emission pathways that would lead to stabilization, but include alkalinity enhancement.” The reference simulations follow the adaptive emission reduction approach (see explanation in the methods). And it does negative emissions, if the climate becomes too warm and the carbon budget is exhausted. The spatial emission field is scaled by the adaptive emission reduction approach and when the climate becomes too warm, the emissions turn negative. So you could say it does Direct Air Capture with perfect storage. Both the OAE and the reference simulation have the same emission forcing (Fig. C1) including the negative emissions. We added another sentence to the description of the AERA approach: ”If temperatures overshoot, the algorithm responds by prescribing negative emissions.”

Figure 3. The word “anomaly” is missing from the caption in (a).

Response: Added.

Figure 6. if possible, consider including the frame of reference in the caption (e.g., positive means loss from the atmosphere) in the caption.

Response: That is a good point, we have added "Positive indicates additional ocean carbon uptake."

References

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