

Response to Reviewer 1's comments for Assessing Carbon Dioxide Removal Through Global and Regional Ocean Alkalinization under High and Low Emission Pathways by Lenton et al

*Comments Reviewer 1*

*Minor Comments*

*Abstract: L19-21: Be specific, what changes are seen? In what parameter?*

Added "in alkalinity"

*L21-22: Not quite sure what that means.*

The sentence now reads: *Globally, while we see that under RCP2.6 the carbon uptake associated with AOA is only ~60% of the total under RCP8.5, the relative changes in temperature are larger, as are the changes in pH (140%) and aragonite saturation state (170%).*

*L22-23 The change in saturation state is ambiguously describe, refer specifically to changes in omega.*

With respect the actual values are listed in the body of paper, and to list all of the values here would make the abstract too long.

*L28 It's left a little open ended here, you could be more specific with the regional response. It is one of the more important findings from the experiment.*

We would love to but given the length of the abstract we feel that we are somewhat limited in terms of space. But we have tried to be a little clearer, the last sentence of the abstract now states:

*Finally, our simulated AOA for 2020-2100 in the RCP2.6 scenario is capable of offsetting warming and ameliorating ocean acidification increases at the global scale, but with highly variable regional responses.*

*Introduction: Good introduction. Clearly explains why we need CDR and more specifically AOA. Also gives a description of ocean acidification and how AOA works.*

**Thanks**

*L50: 'Including through coral bleaching' a little chunky, maybe remove 'through'*

*We have removed this statement, it now states: While warming represents an imminent global threat which is already significantly impacting the natural environment (Hughes et al., 2017), ocean acidification poses an additional and equally significant threat to the marine environment.*

*L54: Could you say something about the changing Revelle Factor, and the potential for AOA to impact this?*

*We have now added the statement to the text: As CO<sub>2</sub> is taken up by the ocean it changes its chemical equilibrium, reducing the carbonate ion concentration and decreasing pH, collectively known as ocean acidification.*

*We have also added statement later in the introduction to say:*

*Artificial Ocean Alkalization (AOA), through altering the chemistry of seawater, both enhances ocean carbon uptake (thereby reducing atmospheric CO<sub>2</sub>), while at the same time reversing ocean acidification and increasing the buffering capacity of the ocean.*

*L148-150: simply states "impact" which could be a bit vague. Could go in further and state that they will be investigating the impact on the "carbon cycle, global surface warming (2m surface air temperature), and response and ocean acidification response to the 4 different AOA experiments under the high (RCP8.5) and low (RCP2.6) emissions scenarios." Which is stated in lines 207-210. Regarding my comment above, it is worth exploring the potential experiment space, magnitude of alkalinity addition, location, emission scenario, and the resulting impacts site specific/regional/global/ open ocean/coastal etc. What parts of this picture does your model/this paper deal with, what has already been done by others, and what is left to do? are other models needed?*

The goals of this study of this focus on the global response to regional and seasonal AOA, therefore we don't explore are best ways to ameliorate local conditions through AOA.

Regarding question of whether to explore experimental space further – the answer is yes there is a lot of work that needs to be done (please see the review by Renforth and Henderson (2017)) and these results are put into this context in the Results and Discussion section. AOA will also have addressed as part of the Carbon Dioxide Removal Model Intercomparison Project (CDR-MIP), which we are involved in.

We have now modified the paragraph to now say:

*In this work, we use a fully coupled ESM (CSIRO-Mk3L-COAL), which includes climate and carbon feedbacks, to investigate the impact of AOA on the carbon cycle, global surface warming (2m surface air temperature), and ocean acidification response to the global and regional AOA experiments under the high (RCP8.5) and low (RCP2.6) emissions scenarios*

*Methods:*

*Model seems appropriate for the scope of this paper. Clear description of the experimental design which seems appropriate to answer the research question proposed in the introduction. Could explain what the model outputs are? Also should mention the testing for seasonality? (mentioned in lines 538-554)*

This model has been assessed in a number of studies already cited here and the outputs are consistent with standard Earth System Model outputs. As stated above the key outputs we consider are surface air and ocean temperature, and changes in the surface pH and aragonite saturation state. We also describe in the methods sections a number of other model prognostic variables (lines: 153-168) and provide references to individual model papers that describes components of the CSIRO Mk3L-COAL earth system model.

*L162-164: Do you expect this assumption to hold up under elevated alkalinity? Could the rain ratio change?*

Probably, this is already addressed in the lines 445-460, and studies suggest a small feedback.

*L204: Fair assumption, but it is worth pointing out that alkalinity manipulation could be from carbonate dissolution or NaOH addition which would not induce and impact from iron*

*and silicate. You are testing the fundamental impact intrinsic to all of these methods of C sequestration.*

We agree, the sentence now reads:

*We do not consider the biogeochemical response to other minerals and elements that can be associated with the sourcing of alkalinity from the application of finely ground ultra-mafic rocks such as olivine and forsterite, nor dissolution processes required to increase alkalinity (e.g. Montserrat et al., 2017).*

*Results and discussion:*

*L208 – 209: the sentence doesn't make sense, a typo somewhere?*

Yes, we have now removed *and response*

*L215: Why have you chose this addition rate? Also, should alkalinity not be expressed in equivalents rather than moles (and throughout)?*

As stated, this value is very close to that used by Keller et al (2014) following Kohler (2014), who estimated a value of AOA based on globally shipping. While this allows a comparison of simulated values and a quasi-physical value, our work is more focussed on comparing and contrasting the responses to AOA for low and high emissions to regional and seasonal AOA. Regards units we have followed the convention used by Zeebe and Wolf-Gladrow (2005) and followed Keller et al (2014) and to ensure consistency with previous work.

*L218-221: Fascinating, but why was the response different?*

This is now addressed in the discussion

*L232: "at" is missing*

Addressed

*L239: I think 'an overall' is missing before 525 ppm in the brackets*

Added

*L241: could you also give this as a % similar to how you did for RCP8.5*

This is a good comment – however. This doesn't really make sense as the atmospheric value at end is less than at the beginning.

*L251-254: This is really important...why was there an increase in export?... The 1% is an important outcome because it is the 'efficiency reduction' on the overall engineering system design.*

Firstly, this is a really small number (<1%) and as stated occur in the Arabian Sea. In section 3.2.3 it now reads:

*The very small changes in export production in RCP2.6 were located in the Arabian Sea (not shown), likely driven by enhanced mixing in this region.*

*Could tables 1-3 be summarised in one table? I think it would make things a little clearer.*

This is a good and we have now combined these three into a single table

*Line 331: could be explained more clearly rather than just "due to the Revelle factor" (see previous comment)*

We have now rewritten this section to be clearer, it now states:

*In the 2020-2100 period, AOA under RCP2.6 led to much larger increases in surface pH and aragonite saturation state, more than 1.3 times, and more than 1.7 times that of RCP8.5 respectively (Table 4). These changes reflect the differences in the mean state associated with high and low emissions, specifically the difference between Alkalinity and Dissolved Inorganic Carbon (ALK-DIC), a proxy for ocean acidification (Lovenduski et al, 2015). As the values of DIC in the upper ocean are larger under RCP8.5 than RCP2.6, the difference between ALK and DIC (ALK-DIC) is smaller and the chemical buffering capacity of CO<sub>2</sub> or Revelle Factor (Revelle and Suess, 1957) is less. This means that, for a given addition of ALK the increase in the upper ocean DIC will always be greater under RCP8.5 due to its reduced buffering capacity. Consequently, the changes in ALK-DIC with AOA are greater under RCP2.6 than RCP8.5, which translates to greater increases in pH and aragonite saturation state.*

L374: *'This reflects the fact that' should be rewritten 'This is caused by the subduction processes..' or something similar.*

We have now added *through subduction* to this statement

L396: *'Quite low', how low?*

We have now removed *Quite*

L445-447: *But could you speculate as you have in the previous sentence? How much would export have to change to make a material difference?*

We would not like to speculate to do this as many of the processes are not well understood, instead we reference Matear and Lenton (2014) for a discussion of these processes and feedbacks.

L507: *This doesn't quite ring with your abstract, which suggests that ocean acidification would be mitigated. Would it not partially ameliorate the impacts?*

The last line of the abstract refers to low emissions, so they are consistent. Yes, it would ameliorate some of the impacts under RCP8.5, as shown, but its impacts would much less than under RCP2.6.

L599: *'Interestingly' is used a bit too often, it gets a bit jarring.*

Removed

*Figures:*

*All Figures are clear. Slightly too many for this type of manuscript. Could some be moved to the supporting information? Figures 11-12 are not referred to in the text.*

We feel all figures are warranted, and we have added references to figures in the text.

