

Interactive comment on “Assessing Carbon Dioxide Removal Through Global and Regional Ocean Alkalization under High and Low Emission Pathways” by Andrew Lenton et al.

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Response to Reviewer 2's comments for Assessing Carbon Dioxide Removal Through Global and Regional Ocean Alkalization under High and Low Emission Pathways by Lenton et al

Reviewer 2: Major comments:

Major comment 1: The changes in the land carbon uptake (table 2) in the AOA simulations based on the RCP2.6 are around 4 times higher than those of the simulations based on the RCP8.5. This is an important aspect because the variations in these

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carbon fluxes determine the final state of the climate. That is why I think that these results should be discussed properly and the cause of this differential behaviour should be explained.

These differences are due to 2 main factors: (i) the temperature differences between RCP2.6 and RCP8.5. The mean SAT cooling over land under RCP2.6 is much larger (2x) this means that the decrease in carbon uptake would be larger RCP2.6 than RCP8.5; and (ii) as seen Zhang et al (2014a), the climate sensitivity of the land carbon-climate feedback under higher emissions is lower than other models' due to nutrient (N&P) limitation. This sensitivity in part explains why the response of the land carbon cycle is about half that reported in Keller et al (2014).

The text now states: ...On the land, in the RCP8.5 simulation there was a smaller reduction in carbon uptake than in RCP2.6 (Table 1), due to larger decreases in surface air temperature (SAT) over land in RCP2.6 than RCP8.5 (~2x; see Section 3.1.2). The land carbon cycle response was also smaller under high than low emissions due to nutrient limitation being reached, thereby limiting the effect of CO2 fertilization (Zhang et al, 2014a).

Major comment 2: The statements given between the line 285 and 289 are really confusing. On the one hand, it reads as the temperature change in the RCP8.5 experiment is higher than the one associated with the RCP2.6, which is not what I see in the numbers. And on the other hand, making reference to "potentially reflecting feedbacks" in order to explain this cooling signal does not help to understand the signal. Instead, it confuses the reader. Please explain properly how these feedbacks affect the results.

This was a mistake and has now been corrected. We have now clarified the text and removed the reference to feedbacks which was not correct, please see the comment below showing that the disparate responses are primarily due to differences in atmospheric CO2 growth rate, please the response to Major Comment 3 (next) for more detail.

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Major comment 3: The reduction in atmospheric CO₂ concentrations by 2100 associated with the AOA scenarios under RCP8.5 emissions (app. 84 ppm) is higher than the one associated with the AOA scenarios conducted under the RCP2.6 (app. 40 ppm). Yet, the mitigated warming in the AOA simulations under RCP2.6 is higher than those conducted under the RCP8.5. This is one of the main findings of this publication, however, there is not any discussion/explanation of this result. Only stating what the model delivers is not enough, since it could be a model artefact, the signal might not be caused by AOA, etc. The RCP8.5 and 2.6 scenarios have atmospheres with quite different levels of CO₂, which might lead to differences in the CO₂-forcing response to changes in CO₂ levels. Not only that, but also the RCP8.5 and 2.6 scenarios differ in the assumed land use and the sea ice extent by the end of this century. This might also cause changes in albedo and therefore in the cooling response due to changes in forcing.

There are a number of mechanisms that may explain the differential response of the cooling which is larger under RCP2.6 than RCP8.5, these including the CO₂ vs outgoing long wave radiation (OLR) log relationship, and land and ocean albedo changes. We find that while these may play a minor role, the major driver of these differences are due to differences in atmospheric CO₂ growth rate between RCP2.6 and RCP8.5.

We have now added the following statement to the text: ...In the period 2081-2100 we see larger mean changes in SAT under RCP2.6 than RCP8.5 primarily due to differences in atmospheric CO₂ growth rate. Krasting et al. (2014) showed that the slower rate of emissions, the lower the radiative forcing response. This occurs in response to the timescales associated with the uptake of heat and carbon. Consequently, under RCP8.5 the atmospheric CO₂ growth rate is much faster than RCP2.6, leading to a strong radiative forcing response. This explains why, despite a larger reduction in atmospheric CO₂ concentration under RCP8.5, the biggest reduction in global mean SAT occur under RCP2.6...

Ref: Krasting, J. P., Dunne, J. P., Shevliakova, E., and Stouffer, R. J.: Trajectory sensitivity of the transient climate response to cumulative carbon emissions, *Geophys Res Lett*, 41, 2520-2527, 10.1002/2013gl059141, 2014.

Major comment 4: Between the lines 325 and 334 an explanation to the differential pH and aragonite saturation state responses between simulations is given. This explanation seems confusing and it refers to the other main finding of this publication. Because of this I think that it requires some supporting figures (which could be added into the supplementary information) and some extra work in order to clarify the message. I suggest to look at the buffer factors and the effects of AOA under the two different DIC/ALK regimes associated with the RCP8.5 and 2.6 scenarios. More information can be found in the paper by Egleston et.al. (2010) (<http://onlinelibrary.wiley.com/doi/10.1029/2008GB003407/abstract>). We have rewritten this paragraph to better capture our message make it more accessible.

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 CO₂ 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.

Minor comments: L16, L27 and L561: "is capable of" gives the impression that AOA has not real big limitations to be implemented which is not the case, please modify the wording This wording is correct, AOA is capable and is analogous to alkalinity addition

that occurs over geological timescales and this has been hypothesised to play a role in glacial-interglacial timescales.

L18, L19: there are acronyms which the reader might have never seen in the abstract, please spell them out or remove

We have now spelt out CO2 and RCP

L25: "lower" and "higher" emissions than what? I think that you meant "low" and "high"

This is correct, we wanted to be more generic than just RCP 2.6 and 8.5, particularly as Shared Socioeconomic Pathways (SSPs) will be used CMIP6.

L26: our simulations show that AOA during the period ... ; in any case I do not think that this very last sentence in the abstract is needed

With respect, we think that this is an important statement to make.

L46: ... could help to ...

Corrected

L53-54: CO2 that enters the ocean does not react with seawater to reduce the carbonate ion concentration, please reconsider this statement and use correct grammar

This has now been changed to say: As CO2 is taken up by the ocean it changes its chemical equilibrium, reducing the carbonate ion concentration and decreasing pH, collectively known as ocean acidification.

L59: ...changes in calcification...

Corrected

L60: are you sure that ocean acidification alters nutrient availability

Yes e.g. Shi et al (2010) Shi et al (2010) Effect of Ocean Acidification on Iron Availability to Marine Phytoplankton, Science 327, 676 (2010);

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L62: please change order of publications

They are already in name order

L69: semicolon needed?

Removed

L77: weathering of minerals play a crucial role in modulating the state of the climate in geological timescales, please write an assertive statement

Removed may

L91: reviewed

This should be present tense, I believe

L92-95: way too long sentence, please simplify and split it

This has now been split

L98: Did Kohler used one or several models? Changed to singular

L110: ocean only without the hyphen

Corrected

L110: and they showed

Corrected

L111: high CO2 emission

Corrected

L114: also concluded that

This should be present tense, I believe

L115, L118, L131, ...: impacts of

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Changed

L124: from a high

Changed

L126: it would be required

Changed

L127: and it would come

Changed

L134: 78 ppm between brackets might look better

Changed

L134: a net atmospheric cooling

Changed to surface air temperature

L139: "to be very large" - (very) large in what respect? please clarify

The sentence now reads: Capturing these feedbacks is critical as they have the potential to significantly increase atmospheric CO₂ concentrations (Jones et al., 2016).

L141: currently assume (instead of "utilize")

Changed

L141 to L145: way too long sentence, please simplify and split it

Changed to: Furthermore, the feasibility of these approaches which are increasingly questioned due in part to limited land (Smith et al., 2016), whereas the potential CDR capacity of the oceans is orders of magnitude greater (Scott et al., 2015).

L149: and surface warming L149: questions L147 to L152: I think that the novelty of this study could be better emphasise. In any case, this last paragraph is crucial and

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therefore it should be improved since it does not read well.

The above three comments have been addressed in response to Reviewer 1 and the paragraph now reads: 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.

L158: extra dot after citations?

Changed

L160, L163, ...: please remove the brackets in those citations which are subjects of the sentences, this occurs several times in this manuscript

Changed

L164 to L166: does this sentences really add any relevant information? Such a feature of the model is basic to conduct this study

Yes, we agree but it does provide confidence in the tool we are employing in this study – as seen by Review 1's comments

L171 to L172: the land carbon cycle currently has too many uncertainties to state something in such an assertive manner, please consider to modify this or even remove it

We have removed realistically

L185: from 2006 onwards, ...

Corrected

L186: corresponding to the Representative ...

Corrected

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L218: Subpolar addition

Corrected

L232: is seen in 2100

Corrected

L233 to L235: if you mention this feature of the modelling tool, please explain the associated consequences for the simulations of AOA

We have discussed these results in the manuscript and identify why the sensitivity of the land carbon uptake, particularly under high emissions is less than other studies.

L242 and L256: "more than compensates" and "more than offset" are really confusing ways of describing the obtained values, please clarify

We have removed more than in both of these instances

L247: 50% instead of 1.5 maybe?

Corrected

L253: total ocean uptake ...

Corrected

L254 to L258: this explanation reads really confusing, please clarify

This has now been changed to say: The simulated cooling drove both a reduced net primary production, leading to reduced carbon uptake, and an increase in carbon retention associated with a reduction in heterotrophic respiration. However, overall, the net decrease in land carbon uptake means that in the response to AOA globally the reduced net primary production dominated.

L266: addition studies such as Ilyina ... which demonstrated ...

Corrected

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L270: 181 PgC is in ... (instead of was)

Corrected

L277: I think the authors meant "positive denotes enhanced uptake" (instead of "negative")

Yes – this is corrected thank you

L288: "large" twice in the sentence

Corrected

L294: "projected" instead of "anticipated"

Corrected

L295: why is this publication here cited?

Removed

L298: standard deviations with respect to what? what is this (1 - sigma)? Please clarify

The caption has now been improved, and now reads: Table 1 The differences in global mean surface air temperature in the period 2081-2100 (2090) and associated standard deviation (1- σ) (K; SAT; 2m) for the four different AOA experiments for each emission scenario, relative to the same emission scenario with no AOA.

L302 to L304: please consider to reformulate these sentences since "variability" might refer to many different things (e.g. inter annual, inter model, model internal, ...). In any case I think that "variability" is not really the term to use since what is described here are differences between simulations.

The sentence now reads: Within each of the scenarios, there are some differences in the magnitude of the cooling within the four different AOA experiments; however, these are smaller than the interannual variability over the last two decades of the simulations.

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L308: mean surface cooling

Corrected

L318: What is the point of this statement and citation? The pH and aragonite saturation state correlate really well as I can see in the figures.

Yes but the impacts are different and this motivates why we are interested looking at both aragonite saturation state and pH.

L321: despite the return

Corrected

L344 and L377: the citation here to Groeskamp et.al. seems unfounded

Removed

L348 and L349: Please elaborate on this so that the reader understand the context, e.g. discuss how this change in pH might (or not) matter, ...

We have modified this sentence to now say: To put these changes into context, the estimated decrease in pH since the preindustrial period is 0.1 units (Raven et al., 2005), and is responsible for already detectable changes in the marine environment (Albright et al., 2016).

L380: How can one of the experiments (AOA_ST) reflect the timescales of the circulation of the subtropical gyres? Please explain this.

This sentence now reads: In the case of AOA_ST, this reflects the timescales associated with the longer residence time of upper ocean waters in the subtropical gyres.

L382: ice covered (instead of "non-ice-free")

Changed

L386: by 2100 (instead of "in")

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Corrected

L387 and L388: please clarify this, is not understandable

This is now clarified to say: Specifically, for AOA_G we see 31% remains in the upper ocean and for AOA_T and AOA_ST: 34%, while for AOA_SP: 22-24% remains in the upper ocean which (as anticipated) is lower than in other regions.

L404: ...seen in the...

Corrected

L421 to L425: please work on the grammar of these sentences

Corrected

L442: ... in the ratio ...

Corrected

L444: Dot missing

Added

L445: ... remain poorly...

Corrected

L457 to L459: why do you obtain this result?

We have added: likely driven by enhanced mixing in this region.

L463: remove (SAT)

Removed

L468 to L470: why do you obtain this result?

This very much reflects the period over which the mean changes were calculated, and

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the simulated large variability in SAT in this region, which now stated in the text.

L538 to L554: why no figures are shown in this section on seasonality to support this discussion? Also, only AOA is implemented in the summer season under RCP8.5 emissions, which does not seem to me enough to explore the effects of seasonality.

This is a little confusing as the Reviewer wishes us to remove figures and now requests more. We don't present results here, as it is a sensitivity experiment, rather than a major result.

L560: please remove (COP21)

Removed

L593 to L595: What do you mean? Please clarify this.

It now states: However, AOA under the RCP2.6 emissions scenario changes the roles played by the ocean and land in carbon uptake as compared with the scenario of RCP2.6 with no AOA, resulting in a reduced uptake in the terrestrial biosphere and increased uptake in the ocean.

L605: double "that"

Corrected

L620: mention "preindustrial period" and remove (1850) reads better

Changed

L621: cases (subject?) leads ...

Corrected

L633: for the role

Corrected

L638: ...therefore it needs ...

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Added

L642 and L645: Earth system (instead of earth system)

Corrected L649: please put "e.g. mesocosm experiments" between brackets

Added

Please keep an eye on the format in which the references are given and be consistent with it.

Done

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Please also note the supplement to this comment:

<https://www.earth-syst-dynam-discuss.net/esd-2017-92/esd-2017-92-AC2-supplement.pdf>

Interactive comment on Earth Syst. Dynam. Discuss., <https://doi.org/10.5194/esd-2017-92>, 2017.

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