Biogeosciences
Discussions

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Interactive comment on "Increase in ocean acidity variability and extremes under increasing atmospheric CO$_2$" *by* Friedrich A. Burger et al.

Sarah Schlunegger (Referee)

ss23@princeton.edu

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Burger et. al. presents a clear and logical assessment of projected changes in the variability of ocean acidity and their impact on acidic extremes. The study uses an Earth System Model (ESM) which they demonstrate has historical fidelity with observed acidification trends. The study contrasts future acidity extremes under low- and high-emissions scenarios, all relative to 99th percentile extremes as defined in the preindustrial control simulation. Changes in the duration, frequency, intensity and volume extent of extreme events are presented. Drivers of change in [H+] variability are partitioned into contributions from changes in the mean state and variability of carbon concentrations, temperature, alkalinity and salinity. As noted by other reviewers, the exact decomposition used is flawed and needs revision before publication.

C1

Other than this obvious issue, I have only three broad suggestions which would ready the manuscript for publication in Biogeosciences.

1. As a first assessment of changes in OA extremes, this paper has the opportunity to present simple, conceptual explanations for why those changes are occurring. This is done adequately for the case of [H+] but not for the case of Omega. Why is Omega variability decreasing? Is this largely driven by changes in carbonate chemistry, the way it is for [H+], or are changes in ocean dynamics involved? This has implications for the robustness of the results across other ESMs.

2. Further discussion is needed of why variability changes at the surface differ from those at 200m depth and of why there is strong compensation between the contributions of increasing carbon concentrations and decreasing carbon variability to [H+] variability at depth (9e vs 9f, and to a lesser extent at the surface, 8e and 8f). The striking spatial patterns in Figure 9e and 9f should also be explained.

3. Include discussion of model uncertainty. For example, results that are a direct chemical consequence of invading anthropogenic carbon (e.g. increasing sensitivity of [H+] to drivers) are more likely to be more robust across models than results that are a consequence of changes in ocean physics. ESM2M has less warming and a stronger ocean carbon sink than the majority of CMIP5 models – how might the results presented compare to a model with higher climate sensitivity and less ocean carbon uptake models?

The manuscript is a significant contribution to the field, addresses the pressing issue of ocean acidification, and does so with excellent visualization and explanation. I strongly recommend publication (after the listed revisions are implemented).

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Additional comments and stylistic suggestions

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C2

L5: number of days where? At each point? On average? Overall occurrence anywhere?

L28: replace 'or' with 'and/or'

L33: define saturation horizon – e.g. Saturation generally decreases with increasing depth, with transition from saturated to undersaturated referred to as the saturation horizon.

L33: add 'can' in front of 'also'... 'can also'

L38: remove 'vast'

L40: add 'also' in front of necessary... 'also necessary'

L45: ...'critical threshold, like undersaturation.'

L50: sentence rearrangement for clarity: 'In laboratory experiments in which deep-water corals are exposed to low-pH waters for a week...'

L53: Start sentence with 'Therefore,'

L61: '...at which higher background concentrations of dissolved inorganic carbon (DIC or C_T) and warmer temperatures produce stronger departures from mean state values for a given change in pertinent physical or chemical drivers.'

L103: Detail about spin-up and control is distracting.

L110: omit 'and', replace with comma

L120: 'year-long' – however these detail is distracting so potentially remove all together.

Figure 1.

» The figure caption (and methods) say that the ensemble mean is removed – however what is removed is actually the departure of the ensemble mean from the preindustrial state. If the ensemble mean itself were removed, then all values at year 1861 would be

~zero. Update description or replot.

» Panel b is presumably derived from panel a, however it is confusing that the variability in panel a contracts during the 21st century, however it is shown to increase in panel b. Please add an explanation in the caption or text.

L230: remove 'we consider'

L240-245: Further and continued clarification that values given are a global average of local changes. With each presentation of a value, indicate it is a global average.

L244: change 'single events' to 'individual events'

L255: Why is high-frequency variability larger at the surface whereas low-frequency variability larger at depth? ... Presumably because the surface has direct contact with the atmosphere, and its chaotic, high-frequency (weather) variability, whereas the deeper ocean experiences stronger low-frequency variability as the ocean acts as a low pass filter on the atmospheres' stochastic forcing (e.g. Hasselmann 1976). Add/include explanation.

L298: insert 200 meters... ' In contrast to the surface, 200 meter [H+] extremes'...

L357-361: C_T increases due to invasion of anthropogenic carbon. But why does ALK change? ALK is not influence by gas-exchange, but by biology or circulation. Briefly explain ALK changes and give reference. 378-379: [H+] variability changes at depth are larger than at surface – is this mostly due to the fact that background C_T concentrations increase with depth, however increased C_T itself is associated with decreased susceptibility to external variability? Figure 8 e) vs f) indicates this is the case. Provide commentary.

Figure 9.

» Panel 9b and 9c bear strikingly similar patterns and magnitudes – where the changes in the mean-state of the drivers is largest and positive, changes in the variability are

also largest and negative. And this is mostly coming from C_T mean (increasing) and C_T variability (decreasing). Is this directly understandable through carbonate chemistry? In a higher DIC world, DIC variations are actually smaller? Or is it that the physical, surface to deep gradient in DIC is weakening with surface invasion of anthropogenic carbon and therefore mixing-related variability is reduced?

» Explain this near-perfect anti-correlation.

» Also, the structures of strong mean and variability changes look dynamical. Potentially the expansion of the subtropical gyres. Explain the spatial structure of the patterns of strong drivers.

» In the appendix, include figures of the pre-industrial and year 2100 concentrations of C_T at surface and 200m depth. The patterns in 9e and 9f are likely related to both the starting concentrations of C_T and the storage of C_T. Figure A4a and A4e show the change in C_T, which resembles the strong patterns of 9e and 9f. Synergies of anthropogenic carbon and background concentrations of C_T may help explain strong structures of 9e and 9f. The strongest temperature changes (A4g) also resemble the strong patterns of 9e and 9f, indicating either dynamical changes or thermal changes are involved.

Line 393: Is the decrease in Omega variability a direct consequence of carbonate chemistry? Or of changes in the variability of the drivers or physical state (e.g. vertical gradient hypothesis stated before)? This is an important distinction, as carbonate chemistry is well constrained (little model uncertainty) whereas dynamical changes have much larger model uncertainty. If reductions in Omega variability are chemically deterministic, then this feature will be relatively robust across models, as most use the same (e.g. OCMIP2, Najjar et al. 2007) protocols for carbonate chemistry calculations. But if it is dynamical, it may not be. Furthermore, if it is chemically driven, and if it is related to the storage of anthropogenic carbon and/or concentration of natural carbon, then contemporary observations and reconstructions of the distribution of natural and

anthropogenic carbon in the ocean could reveal where changes in Omega variance are likely to occur.

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References

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Hasselmann, K. 1976. "Stochastic Climate Models Part I. Theory, Tellus" 28 (6): 473–85. https://doi.org/10.3402/tellusa.v28i6.11316.

Najjar, R G, X Jin, F Louanchi, O Aumont, K Caldeira, S C Doney, J C Dutay, et al. 2007. "Impact of Circulation on Export Production, Dissolved Organic Matter, and Dissolved Oxygen in the Ocean: Results from Phase II of the Ocean Carbon-Cycle Model Intercomparison Project (OCMIP-2)." Global Biogeochemical Cycles 21 (3): n/a–n/a. https://doi.org/10.1029/2006GB002857.