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Discussions

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# Interactive comment on "Is deoxygenation detectable before warming in the thermocline?" by Angélique Hameau et al.

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General:

Hameau et. al. provides a multi-model (CMIP5) assessment of the relative timing of emergence of anthropogenic change in thermocline oxygen and thermocline temperature. To facilitate multi-model assessment of time of emergence (ToE), they provide a new metric, relative ToE. They find that for most of the global ocean changes in temperature emerge prior to changes in oxygen, however for some regions, changes in oxygen emerge prior to changes in temperature. Anthropogenic changes in oxygen emerge prior to temperature in regions where reduced solubility and ventilation work in tandem to reduce oxygen concentrations. In these locations, reduced ventilation also

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slows the propagation of anthropogenic warming signals from the upper ocean into the ocean interior, further contributing to the delay between emergence of thermocline oxygen and temperature.

This paper represents an important contribution to the growing body of mechanistic interpretations of emergence timescales in the global ocean. Additionally, it confronts the known challenge of model-intercomparison with provision of a simple, yet powerful new metric, relative ToE. I recommend its publication in Biogeosciences, but only after minor-to-moderate revision of the text and inclusion of an additional figure to better visualize the regions for which thermocline oxygen robustly emerges prior to temperature.

Sincerely, Sarah Schlunegger, PhD Princeton University Program in Atmospheric and Oceanic Science

Specific:

1. Improve Abstract In the abstract, I would suggest the following rewording to replace some of lines 7-10: Changes in thermocline oxygen emerge prior to changes in temperature because oxygen declines occur due to the confluence (or additivity) of both reduced solubility and ventilation. Otherwise, the abstract could be further streamlined and focused. Feel free to borrow from my summary above.

2. Improve motivation/framing of the introduction Page 3 frames the question of "Which emerges first, physical or biogeochemical variables?" However, this is an ill-formed question, as the chronology of emergence has already been documented to not follow strict temporal separation of physical and biogeochemical variables. For example, Rodgers et al., 2015 evaluates ESM projection of 4 variables and find the following general emergence sequence: pH, SST, O2, NPP – biogeochemical, physical, physical, biogeochemical. Schlunegger et al., 2019, evaluates ESM projection ~20 physical/biogeochemical variables, finding their emergence timescales are separated by their association to either chemical (gas-exchange) or physical (warming) impacts

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of climate change on the ocean, and NOT to whether the variable itself is physical or biogeochemical. Variables that are first-order impacted by increasing atmospheric pCO2 and increased gas-exchange, like DIC, pH etc., will emerge the most rapidly (carbonate-chemistry related biogeochemical). Later, as atmospheric warming propagates into the ocean (physical) warming signals emerge, and quickly after solubility induces changes (like O2sat). Even later, circulation eventually adjust (physical), thereby altering nutrient supply (biogeochemical), and subsequently primary production (biogeochemical), export production (biogeochemical), etc. The broad order of emergence could then be described as 1. Carbonate-chemistry related biogeochemical and biology (hard tissue pump), 2. Surface temperatures and solubility-related variables (like O2), 3. Ocean dynamics, 4. Biogeochemical impacted by ocean dynamics (nutrients, production).

3. Additional methodological explanation required Explanation of how S is computed, and its statistical properties relative to N, should be addressed more clearly. For instance, there are broadly two distinct usages of the term "time of emergence" – the first is to define the point in time at which the ocean state/variable is distinctly out of the range of the pre-industrial state, the second, is to define the point in time at which a forced trend is outside the range of how large natural trends are likely to be. I infer that the first meaning is used here, but that should be made clear.

4. Potentially reordering the figures to improve narrative flow Another immediately odd thing that I see is that Figure 1a and 1b at first glance oppose the main hypothesis of the manuscript. This is just visually the case because O2 has higher model disagreement and T and therefore more area where at least 2 of the models think emergence does not occur this century. However, I know many (mostly senior) scientists who just read the abstract, skim the method and the look at the figures. From this alone, the figures do not tell your story until Figure 6. In fact, Figure 1 is somewhat irrelevant to the stated hypothesis in the introduction. The order of figures could therefore be revised to Figure 2, 3, 6, 7, 8, 1,4,5. With the text also reordered.

5. Additional figure to better visualize regions of ToE(O) < ToE(T) These regions should be better visualized in the paper, potentially in a synthesis map showing locations of ToE(O)<ToE(T) robust across models (could use the 7/9 threshold for example) and/or a figure/bargraph for which regions are aggregated and the average relTOE(O) vs reTOE(T) is ploted for each model. So the figure would have regions on the X axis and ToE(O)-ToE(T) on the Y axis. From there the reader could see the spread in the models as well as pick out regions where it is most likely for ToE(O) to be significantly shorter than ToE(T).

Additional Technical/Editorial Corrections:

Page 1: Line 3: remove word "as" Line 12-14: Simplify sentence with: To normalize across disparate trends and variability of the CMIP5 ensemble, we compute the local ToE relative to the global mean ToE within each model.

Page 2: Line 4-5: correct to remove "and"... adversely affect marine organisms, ecosystems, and the services they provide Line 6: remove "a": ...experienced significant warming Line 9: Make "scale" plural...on regional to local scales Line 13: Slightly awkward jump to discussion of ESMs. Line 17: Remove first phrase, "Concomitant with ocean warming" and just start with "Observation-based studies..." The mechanisms of observed oxygen decline is subsequently explained, so it needn't be partially explained initially. Lines 19-21: Break into 2 sentences and add context. "In subsurface waters, oxygen concentration is also affected by ventilation, remineralization of organic matter and air-sea disequilibrium. In the contemporary ocean, oxygen decreases are mostly dominated by a reduction in ventilation and increased consumption of oxygen during remineralization (references)." Line 21: change to... "The largest oxygen declines are located" Line 23: define "late" industrial period. Line 23-24: change to... "Therefore, it is challenging to distinguish human-caused trends from natural variations in the observational record of ocean O2." Line 24: remove "also"... Modelling studies agree on the sign of ... Line 24-26 could be combined instead with 13-16 and form their own paragraph discussing the current state of modeling O2 trends. Line 32: include reference,

" (e.g. Deutch et. al., 2015)"

Page 3 Line 11-12: rewrite..."is critical to understanding contemporary O2 and temperature changes." Line 17-29: rewrite "One study, (Hameau et al., 2019), uses a single model [ which model?], to investigate ToE of temperature in the thermocline, finding that anthropogenic ocean warming emerges much earlier than the O2 signal in low and midlatitude regions. Delayed emergence of changes in O2 is due to the opposing effects of decreases in O2 solubility and O2 consumption. In the high latitudes and the Pacific subtropical gyres, deoxygenation emerges before ocean warming in [ name model]. This occurs because decrease in oxygen solubility are reinforced by increased O2 consumption, leading to strong O2 depletion However, it is unknown if this single-model result is robust across a suite of different Earth system model simulations. Here, we conduct a multi-model study to more broadly test the hypothesis that anthropogenic deoxygenation in the thermocline emerges prior to anthropogenic warming. Since the primary objective is to test the consistency across models of the order of emergence (deoxygenation prior to warming) within a single model, we introduce and use a relative ToE to conduct the intercomparison, rather than the absolute year of ToE. We define relative ToE as..."

Page 5 Lines 1-10: Over what time frame is S estimated? The texts read "Enting, 1987"... Ending in 1987? At first I thought it was a typo but now I see it is a reference. To clarify, maybe state that S is a timeseires that extends from pre-industrial to 2100 (If I am understanding correctly). Secondly, with what "fitting?" –linear fit, polynomial, etc.? Perhaps the word "fit" should be excluded, if it is in fact meant to just say that the time-series is low-pass filtered. Line 20/21: change request to require and is to are: "We therefore require that ToE values are defined for at least seven out of nine models to compute the multi-model statistics (median and spread)."

Line 24: New section, entitled "Separating mechanisms of oxygen change" or something like this.

Line 24-25: Potentially rewrite: To diagnose processes driving the simulated changes in ocean O2, the direct thermal/solubility component of change (O2sat) can be isolated from the total O2 change. The residual, Apparent Oxygen Utilization (AOU), represents the summation of all non-thermal changes, including those resulting from changes in ventilation and remineralization.

Page 9 The early emergence of T in the Eastern Equatorial pacific should be discussed, and if possible, mechanistically explained. At first glance, it is surprising that an area of such interannual variability at the surface can have relatively little variability at intermediate depths. Line 20: remove word 'typically'

Page 10 Line 11: remove word 'surprisingly' Line 12: what is the confidence interval referenced? Is this references figure 1e, the multi-model spread? If the medium relTOE is 10 and the spread is also 10, then what does "confidence interval" mean in this context? And in that case, a confidence interval value of 1 is not "high". Usually confidence interval terminology is used to describe the probability of rejecting of a null hypothesis. The implicit hypothesis of the statement would be that in the CMIP5 ensemble, this region's relTOE(O2) does not significantly differ from the global average TOE(O2). Potentially a better way to convey this is to state that the multi-model ensemble agrees that the North Pacific represents a region for which emergence timescales are representative of the globally-averaged emergence timescales? Line 15-16: remove sentence that begins "Using". If not, then replace with... "allows for more equitable comparison of projections of CESM with those of lower sensitivity / higher variability models (Figs. 3 and 2)." [because we cannot define high-sensitivity as a 'bias' since we do not know the sensitivity of the Earth's climate yet]

Line 19-20: remove first 2 sentences, and begin with: "Broadly, temperature changes are..."

Line 27: "Model disagreement on the relative timing of TOE(o2) and TOE(T) is highest in the Atlantic..." A figure that bins the regions and computes regional SD across

the models for the quantity ToE(T)-ToE(O2) would be useful. Then you could make statements about the probabilities of certain regions following your hypothesis. For example, the Atlantic certainty does not, but others may. It would give some better spatial insight into where the distributions of Figure 8 are occurring.

Line 27-28: The discussion of the subtropics sounds like an extension of the discussion of the Atlantic. It should be made clear that you are now talking more broadly about the subtropics globally (I think) or still just discussing the Atlantic.

Page 11 Line 1: remove "it is striking that" and later correct to "typically show a decrease" Line 15: replace "noticeable" with "notable" Lines 1-15 are understandable but could benefit from some heavier rewording and condensing."

Line 17: "leading to relatively smaller changes in [O2]"

Line 21: rewrite to be specific: "anthropogenic change in temperature is detectable earlier than anthropogenic change in O2 most of the global ocean"

Page 12 Line 5: "trend" should actually be "change" Line 5-6: Rewrite "Both the magnitude of anthropogenic change and internal variability are model dependent, rendering the absolute year of ToE (strongly*) model-dependent*. Evaluating differences in absolute year of ToE, however, can obscure important model agreement upon the spatial patterns and progression of emergence within a multi-variable framework. We therefore introduce a new metric. . ."

*However, I note a recent NCC paper (Nijsse et. al., 2019) that argues that there is a correlation (and mechanistic relation) between climate sensitivity and decadal variability. Presumably if there is compensation between the two, then ToE could be relatively more robust across models than S or N.

Line 9: "within a model" is misleading – because this sounds as if the models are normalized by some external factor, say by taking "temperature of emergence" (the amount of global warming required for a signal in any chosen variable to emerge). I

think you could add a qualifier, and way "signal emerges relatively early or late relative to the signals global average in the given model."

Line 12: Replace short-coming with limitation or caveat

Line 14: Remove "Perhaps not surprising,"

Page 13 Line 16: Is it known why subtropical gyres in the Atlantic and the eastern equatorial Pacific have elevated noise? Please include. Line 23: Add word "spatial" before pattern. Lines 25-27: Rewrite: Even though the internal natural variability is low in the tropical regions, the O2 signal does not emerge from the noise, so is the signal."

Line 30: add "relatively" before "strong".

Line 35: change "highly" to "significantly"

Page 14 Line 1: remove "largely", if needed replace with "significantly" Line 2-3: Rewrite: "ToEs computed from CESM1.0 projections, for example, differ by many decades in absolute terms from other CMIP5 models, mostly due to a very weak internal natural variability." Line 3-4: Rewrite, something like "To extract valuable insights as to the relative spatial and temporal features of emergence across models and variables, we introduced. . ." However this notion is redundant with previous page so it could be excluded altogether or merged.