

Interactive comment on “Was the North Atlantic Ocean well-ventilated during Oceanic Anoxic Event 2 in the mid-Cretaceous?” by I. Ruvalcaba-Baroni et al.

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We thank anonymous referee #1 for constructive comments and kind words regarding this manuscript. Below are our responses to the specific comments made by the referee.

1) *P13237, lines 6-8: There is actually some evidence for seafloor anoxia in the open ocean prior OAE2. DSDP site 105 shows a succession a green claystone and black shales with TOC up to 8% and high HI before OAE2 (see Kuypers, et al., 2004, Figure 4).*

Reply: The OAE2 data for DSDP site 105 from Kuypers et al. (2004) were already
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included in Table S1, but we indeed overlooked the TOC data for the pre-OAE2 sediments shown in Figure 4 of the Kuypers paper. We now include these data in our compilation and have modified Table S1 and Figure 1 accordingly. We also have modified the text on P13237, which now reads:

“Strong regional variations are observed in organic carbon contents in sediments deposited prior to and during OAE2 (Fig. 1). Prior to OAE2, sediment organic carbon contents greater than 5 wt% and black shale formation are observed in the southern part of the proto-North Atlantic. At one site in the northern Atlantic, organic-rich black shales alternate with green clay stones, indicating periodic bottom water anoxia (Kuypers et al., 2004). Sediments from other parts of the basin are relatively organic-lean with concentrations below 1 wt%. During OAE2, the areas where organic-rich sediments were deposited expanded to include the northern and north-eastern coastal areas and more continuous deposition is observed at deep basin sites.”

2) *P13232, lines 15-16: In the abstract it is mentioned that the model results are “compared to ... proxies for photic zone euxinia and bottom water redox conditions”. Though the data showing evidence of euxinia are described in section 2.2 (biogeochemistry), there is actually no comparison with the model results, which makes the statement in the abstract misleading.*

Reply: In fact, we do compare the model results to the data from section 2.2 in the results and discussion. In section 4.1 (page 13248, lines 4-9), we write: “Note that POC/P_{TOT} ratios in this run are lower than indicated by the compilation of data (Fig. 1 and Table 4), suggesting that we are not fully capturing the redox conditions as observed in the proto-North Atlantic during OAE2.”

In section 4.3 (page 13251, lines 17-20), we write: “When compared to the coastal areas, data on redox conditions for deep-basin sites in the central proto-North Atlantic (W1) are scarce (Fig. 1 and Table S1). However, redox proxy data, including POC/P_{TOT} ratios and sediment trace metal contents, are available for 3 sites at water

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depths greater than 3000 m. These are all suggestive of dysoxic and anoxic conditions during deposition.”

In section 4.3 (page 13252, lines 20-24), we write: “With the given circulation, the intermediate waters of the central open ocean (W1i) remain well-ventilated and thus do not develop anoxia. This is in line with the lower abundance of isorenieratane in OAE2 sediments of this part of the proto-North Atlantic (Kuypers et al., 2004; van Bentum et al., 2012).”

We have now added two more direct comparisons in the text of section 4.1:

Section 4.1 (page 13246, line 25), we now write: “At this level of P input, anoxia only develops along the southern coast (W5) of the proto-North Atlantic (Fig. 4a). This is not in line with data on redox conditions for OAE2 since those suggest anoxia in the north-eastern and northern coastal areas and dysoxia or anoxia in the open ocean (Fig. 1b).”

Section 4.1 (page 13250, lines 5-6), we now write: “...anoxia in the proto-North Atlantic, as deduced from observations (Fig. 1b), can only be reached when...”

Additionally, we have added a colour bar below each basin in Figure 4a representing the oxygen concentrations expected from observations in each region. We have added a new sentence in the caption of Fig. 4 which reads as follows:

“The colour bars below the x-axis indicate the oxygen conditions for each basin as deduced from observations for OAE2 (Fig. 1b) where dark red = euxinic/anoxic, orange = low oxygen/anoxic, blue=low oxygen/oxic, gray = uncertain.”

We now refer to Figure 4a to further highlight the comparison between model and observations in page 13252, lines 5-7.

3) *P13235, line 9: The model which is used in this study, is a box model and does not capture the resolution presented in Figure 1. Instead of “we use” which leads to think*

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that “the model uses”, the authors should be more general here describing what is known about the bathymetry and paleogeography reconstruction of the Cenomanian-Turonian period based on the reconstruction of Topper et al. (2011).

Reply: We have changed the sentence to “The bathymetry shown for both intervals (Fig. 1) has been reconstructed by Topper et al. (2011), based on earlier work by Muller et al. (2008) and Sewall et al. (2007).” We have also added the reference to the work of Topper et al. (2011) in the first line of the caption of Fig. 1: “Bathymetry of the proto-North Atlantic a) prior to OAE2 and b) during OAE2 as reconstructed by Topper et al. (2011).”

The details on the known and unknown bathymetric features are already described in detail in the text. We refer to lines 13-17 on page 13235 and lines 1-12 on page 13236. Further details can be found in Topper et al. (2011).

4) *The authors need to clarify how they setup the initial conditions for the their model experiments. Some of the choices for the pre-OAE2 states are not fully justified and it is not clear if the model ocean biogeochemistry is ran to steady state for the pre-OAE2 condition (see details below). This is important as the model results and the assessment of the conditions for the spread of anoxia rely on the initial conditions and the model setup.*

Reply: Regarding the question whether the model was run to steady state for pre-OAE2 conditions, we refer the reviewer to lines 19-20 on page 13239 where we write “The water cycles for both time intervals are described below, as well as the initial reservoir sizes and steady state fluxes for the various elements for the pre-OAE2 proto-North Atlantic.” We provide a point-by-point reply to all detailed comments regarding the initial conditions below.

4.1) *P13241, lines 5-6: What are the evidence that pre-OAE2 ocean concentrations of POC, SRP and O2 is similar to modern values? This choice should be justified.*

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Reply: Because exact concentrations of POC, SRP and oxygen cannot be easily constrained, it is a common approach when parameterizing ocean biogeochemical models for the past ocean to use information for the pre-anthropogenic modern ocean (e.g. Van Cappellen and Ingall, 1994; Monteiro et al., 2012). We have modified the text to make this clear:

To the sentence (page 13241, lines 5-9) “Initial reservoir sizes of POC, SRP and oxygen in the water column for pre-OAE2 conditions are based on typical concentrations in the modern Atlantic Ocean (Sarmiento and Gruber, 2006) and mass-balance constraints.” we have added: “This is a common approach when parameterizing biogeochemical ocean models for the past ocean (e.g. Van Cappellen and Ingall, 1994; Monteiro et al., 2012).”

4.2) P13241, lines 10-17: More info are needed on how the rates of burial are estimated from the observed TOC content

Reply: We have now added a section clarifying how initial POC burial rates were calculated and have replaced the text in lines 10-12 on page 13241: “Rates of POC burial were estimated from POC contents using typical rates of sediment accumulation for the deep sea and coastal zone ($\sim 2 \text{ g m}^{-2} \text{ y}^{-1}$ for W1 and W2 and ~ 120 to $480 \text{ g m}^{-2} \text{ y}^{-1}$ for the other boxes; Middelburg et al., 1997). Calculated rates of POC burial fall within the ranges typically observed in modern continental margin and deep sea environments (Middelburg et al., 1997, Schulz and Zabel, 2006)”.

and in line 27: “Initial oxygen concentrations in the bottom water of each box calculated from the mass balance for oxygen (Table 1) are in line with observations for pre-OAE2 conditions. This indicates that our estimated values for primary productivity (and POC burial) are reasonable estimates at the given oceanic circulation.”

4.3) Also the authors should be more explicit why they choose to prescribe PP for pre-OAE2 conditions but to calculate OAE2 PP in the model experiments.

Reply: In our model study, we wish to assess under what conditions anoxia developed in the proto-North Atlantic during OAE2, using an initial steady state model for the pre-OAE2 North Atlantic as a starting point. In other words, we want to assess how the well oxygenated proto-North Atlantic could have entered a state of widespread anoxia by testing different forcings in our model. Important model forcings that are relevant when studying the transition to OAE2 are changes in sea level, circulation, P input from rivers and from the Pacific Ocean. Primary productivity and the rates of all other biogeochemical processes for OAE2 are calculated from rate laws derived from the initial steady state fluxes for pre OAE2 conditions. Further details on this modeling approach can be found in Rabouille et al. (2001) and references therein.

We have now extended the text on page 13239 (lines 23-24) to include further details on this modeling approach. We have also rearranged the relevant paragraph that now reads as follows:

“A multi-box model describing the coupled cycles of water, carbon, oxygen and phosphorus for the proto-North Atlantic was developed for pre-OAE2 and OAE2 conditions. Our model approach is similar to that used in other box model studies for the modern and ancient ocean (e.g., Rabouille et al., 2001; Slomp and Van Cappellen, 2007; Tsandev and Slomp, 2009). This approach involves the calculation of an initial steady state for the elemental cycles. This is followed by the parameterization of the biogeochemical processes using simple rate laws. The response of the model to perturbation is then assessed (e.g. changes in circulation, nutrient input). Here, we use the initial steady state for pre-OAE2 conditions, apply a perturbation in a model experiment and then assess the new steady state for OAE2 conditions. The water cycles for both time intervals are described below, as well as the initial reservoir sizes and steady state fluxes for the various elements for the pre-OAE2 proto-North Atlantic. The ordinary differential equations describing mass conservation are solved using R, a free software package (R Development Core team, 2006; Soetaert et al., 2010).”

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4.4) *I think using the observed TOC content as a proxy for PP is a really good idea that could be used to constrain the model results for OAE2 as well. Is there a way to include sediment data to constrain the model PP for OAE2 as well as using seafloor anoxic conditions?*

Reply: After the sensitivity analyses of sections 4.1 and 4.2, we attempt at defining a realistic scenario for OAE2 in section 4.3. In the text, we already compare the observations for POC burial in the different basins to the modeled POC burial in the sediment (P13253 line 1-3: “The greatest relative increase in POC burial is observed at deep basin sites in the central open ocean, which is in line with observations for OAE2...”

4.5) *P13241, lines 24-27: The distribution of nutrient and oxygen content in the intermediate and deep ocean depends not only on how fast the ocean circulation is, but also where the deep water formation sites are and how strong the biological pump is. The authors should thus provide justification for lower oxygen and higher phosphate in the Pacific by considering also the location of the deep water formation and the strength of the biological pump.*

Reply: In contrast to what the reviewer writes above, we assume more (not less) oxygen and lower (not higher) phosphate (see line 25). We agree that the location of deep water formation is important and considered that in the design of our experiment. We have now added the following statement in this section of the text to make that clear (page 13241, lines 24-27):

“However, there is an inflow of Pacific deep water, which is assumed to contain more oxygen and less SRP than modern Pacific deep water (Table 2) due to the assumed high rate of ocean circulation. Note that deep water formation in the mid-Cretaceous took place in the North Pacific and Southern Ocean (Trabucho Alexandre et al., 2010). A high overturning is thus expected to lead to the entry of young (i.e. low in nutrient and well oxygenated) waters into the proto-North Atlantic.”

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The strength of the biological pump during the Cretaceous may have been different from that in the modern ocean. Warmer temperatures may have increased the efficiency of remineralization in the water column (increasing nutrients in surface/intermediate waters) and may also have reduced export production (reducing nutrients in deep waters). This would provide further justification for our choice. However, given the uncertainties related to the biological pump in both the modern and Cretaceous ocean, we think it is not appropriate to introduce the subject here.

4.6) *P13242, lines 1-2: It would be good to add a short discussion about what we know about river input at the Late Cretaceous. There is probably not much out there, but at least saying that we know very little will be instructive and support better why the modern flow distribution and concentrations have been picked.*

Reply: We have added a sentence (directly after lines 1-2 on page 13242) mentioning that there is little known about river input in the Cretaceous: “Modern values are used because little quantitative information about Cretaceous river flow and nutrient concentrations is available.” We have also added a reference showing that the hydrological cycle during OAE2 was enhanced: page 13240, line 16: “enhanced hydrological cycle for OAE2 (van Helmond et al., 2013)”.

4.7) *It is not specified in the manuscript if the model is ran to steady state for pre-OAE2 conditions. This should be explicitly mentioned and justified if not ran to steady state.*

Reply: We explicitly mention in the paper that the model for pre-OAE2 is at steady state (Section 3: page 13239, lines 19-20), see our earlier response above. Note that we also mention this initial steady state in lines 23-24 on the same page: “This approach involves the calculation of an initial steady state for the elemental cycles” and in lines 12-13 on page 13240: “...and were calculated by assuming steady state.” In the revised version there is now also a new section named “3.3. Initial conditions for pre-OAE2” (see point 4.8 below). We also have expanded the section on the model approach, see

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our response to point 4.3.

4.8) *The organisation of this section would gain in clarity if the description of the initial conditions is separated from the model biogeochemistry*

Reply: We have now separated the description of the biogeochemical cycles (new section 3.2) and the initial conditions for pre-OAE2 (new section 3.3) and have renumbered the remaining section on rate laws for biogeochemical processes (section 3.4)

The text in section 3.2 and 3.3 now reads as follows:

“3.2 Biogeochemical cycles

The model includes a simplified description of the carbon, P and oxygen cycles. Particulate organic carbon is the only carbon phase in the model. For dissolved oxygen, only changes in intermediate and deep waters are considered, i.e. surface water concentrations are assumed to be in equilibrium with the atmosphere and are therefore, not explicitly modeled. Phosphorus is present as particulate organic P (POP) and soluble reactive P (SRP).

Key processes in the model are primary production, remineralization, export of POC and POP and burial of POC, POP, iron-oxide bound P (Fe-P) and authigenic carbonate fluorapatite (Ca-P) (Ruttenberg and Berner, 1993; Slomp and Van Cappellen, 2007). The exchange of solutes between boxes is coupled to the transport of water.

3.3 Initial conditions for pre-OAE2

Initial reservoir sizes of POC, SRP and oxygen in the water column for pre-OAE2 conditions are based on typical concentrations in the modern Atlantic Ocean (Sarmiento and Gruber, 2006) and mass balance constraints. This is a common approach when parameterizing biogeochemical ocean models for the past ocean (e.g. Van Cappellen and Ingall, 1994; Monteiro et al., 2012). Exchange of oxygen and SRP between boxes is calculated by multiplying the water fluxes by the concentration in the source reser-

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voir... etc.”

5) *This point relates to my previous point about primary production. It is not clear how primary production is calculated in the model for OAE2 relative to pre-OAE2 conditions.*

Reply: All process descriptions, including the rate law for primary productivity are given in Table S6 as indicated at the beginning of section 3.3 on page 13242. Because our parameterizations are largely similar to those described by Slomp and Van Cappellen (2007), we chose to not repeat them all in the text and concentrated on the process descriptions that we altered. We have now included the description of the rate law for primary productivity in the main text, as requested by the reviewer:

“The process descriptions for carbon, oxygen and P cycling in the water column mostly rely on simple first-order rate expressions (Table S6) and are largely similar to those described in Slomp and Van Cappellen (2007). Here, we briefly describe the parametrization of the major processes included in the model.

Primary productivity (PP) in both the open and coastal ocean is assumed to be a function of the available soluble reactive phosphate (SRP), a first-order rate constant (k_{PP}) and the Redfield ratio (C:P = 106:1):

$$PP_{open/coast} = k_{PP} \cdot SRP \cdot 106 \quad (1)$$

Degradation of organic matter under oxic conditions ($CREL$) is assumed to be a function of the available particulate organic carbon (POC) and a first order rate constant (k_{REL}).

$$CREL_{open/coast} = k_{CREL} \cdot POC \quad (2)$$

In intermediate waters that are low in oxygen, degradation of organic matter is assumed

to slow down when oxygen concentrations ($[O_2]$) are below $1 \mu\text{mol L}^{-1}$ and to come to a halt when oxygen is exhausted.”

6) *P13246, lines 16-17: The fact that PP reduces with OAE2 conditions due to a larger ocean volume might be an artefact of the model configuration. Does the volume of the ocean really increase during OAE2 or is the sea level rise more a result of lifting of the oceanic seafloor due to volcanic activity?*

Reply: Sea level rise during the Cretaceous is generally attributed to glacioeustasy (e.g., Gale et al., 2002; Miller et al., 2005). Additional contributing factors include thermal expansion of ocean water masses (Schulz and Schäfer-Neth, 1997) and periodic changes in continental lake and groundwater storage associated with monsoonal climate variability (Hay and Leslie, 1990). Most evidence points towards eustatic sea level change during the Cretaceous and an increase of the volume of the ocean during OAE2. While the rise of the sea floor may have affected sea level, it was thus not the dominant factor.

We have now added a reference to the work of Gale et al. (2002) on page 13245 line 9-10, directly after “rise in sea level and associated expanded continental shelves”.

7) *P13249-13250: Because the Pacific deep water concentrations in oxygen and SRP have a big impact on the proto-North Atlantic anoxia, it is important to add some discussion here about why there might be less oxygen in the Pacific during OAE2 and where the extra deep Pacific SRP comes from. Is it related to the river input? One interesting aspect would be to think about if the P input (river+P regeneration ...) can be higher in the Pacific than in the North Atlantic Ocean during OAE2 and if that is enough to fuel the North Atlantic afterwards.*

Reply: We have added a brief discussion about what could have increased the SRP and lowered the oxygen in Pacific bottom waters.

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“...Whether the bottom waters in the Pacific Ocean were anoxic, remains uncertain, however. From experiments E1 and E4, we conclude that, given the vigorous circulation of Topper et al. (2011), anoxia in the proto-North Atlantic, as deduced from observations (Fig. 1b), can only be reached when assuming a high external P input and inflow of low oxygenated waters from the Pacific Ocean. Because mid-Cretaceous bottom water temperatures in the Pacific Ocean were higher than today, lower oxygen concentrations and higher rates of remineralization than in the modern Pacific Ocean are a possibility. This could have increased nutrient availability and reduced oxygen concentrations, activating enhanced P recycling. Even with this high input from the Pacific Ocean, it is difficult to obtain anoxia in the central open ocean (W1) suggesting that the ocean circulation assumed here may be too vigorous.”

8) *Can the authors emphasize more on the results in relation to P regeneration? An experiment with and without this process would be interesting for instance to see the effect of P regeneration on the spread of anoxia.*

Reply: We refer the reviewer to page P13251, lines 1-5 where we explicitly discuss the relatively limited role of P regeneration for the spread of anoxia at the basin scale in the sensitivity analyses. We also refer the reviewer to P13253, lines 8-14 where we discuss in more detail the role of P recycling in the basin in our final experiment. Figure 8 shows the relevant rates of enhanced P recycling linked to the anoxia per box. As indicated in the text, enhanced P recycling is important for the spread of anoxia in the coastal ocean but not in the open ocean because of the specifics of the circulation in the proto-North Atlantic.

9) *A discussion about the limitation of the lower spatial resolution would be good. This is a box model and it would be interesting to see what the authors think if their results would hold in a 3D ocean model*

Reply: We cannot predict what the results would be if we had been able to use a 3D

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biogeochemical model. We suspect that the results will be sensitive to the location of the upwelling regions and the fate of the inflowing water from the Pacific. For a detailed discussion of the pro's and con's of box models and 3D models, we refer the reviewer to Ridgwell et al. (2007; "box models continue today to be the tools of choice for many questions involving processes operating on time-scales of about 10,000 years or longer such as those involving ocean-sediment interactions and weathering feedbacks").

To make clear that we consider the 3D modeling of the biogeochemistry proto-North Atlantic as an important future step, we have now added the following sentence to line 7 on page 13254: "Future work should also concentrate on the development and application of 3D biogeochemical models for the proto-North Atlantic that include sediment processes and coastal zone dynamics."

10) *It would good also to comment on the model results in relation to previous similar modelling studies such as Flögel et al. (2011) and Monteiro et al. (2012)*

Reply: We already referred to both modeling studies in our paper and included a comparison to the results of Monteiro et al. (2012) on page 13249, lines 14-16 and page 13251, lines 20-23. However, a direct comparison of results is difficult because in both of these other models a representation of the coastal zone is lacking. Also, both studies concentrate on the global ocean and assume a relatively coarse geometry for the proto-North Atlantic. In the study of Flögel et al. (2011), for example, the proto-Atlantic is included in their 3-box representation of the "Tethys". In addition, Flögel et al. (2011) assume that the C:P ratios of phytoplankton are variable and increase under high pCO₂, while in our model we assume a constant Redfield ratio.

We now have expanded our discussion of the results of Monteiro et al. (2012) and also more specifically discuss the approach and results of Flögel et al. (2011), Page 13252, line 24:

"Low oxygen conditions in bottom waters of the deep basin without a stagnant ocean

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circulation were also successfully reproduced using global models for mid-Cretaceous biogeochemistry by Flögel et al. (2011) and Monteiro et al. (2012). Note, however, that both models do not contain an explicit representation of the coastal zone. Also, both models do not capture the regional circulation pattern in the proto-North Atlantic in the same detail as in our model. Finally, a critical assumption in the model of Flögel et al. (2011) involves the increase in planktonic C:P ratios under high pCO₂ based on mesocosm experiments.”

Minor comments:

11) *P13234, lines 5-7: Add “in the sediments”*

Reply: The enhanced recycling takes place both in the sediments and the water column. We now included a reference to the work of Jilbert et al. 2011 where this is explicitly demonstrated.

“During low oxygen conditions, enhanced recycling of phosphorus (P) from organic matter relative to carbon could have helped to sustain the higher productivity and anoxia (Mort et al., 2007; Kraal et al., 2010b; Tsandev and Slomp, 2009, Jilbert et al., 2011).”

12) *P13236, lines 4-6: for meridional or zonal circulation?*

Reply: Neither. We have now rewritten the sentence as follows:

“A narrowing of the strait could have decreased the water flux from the Pacific Ocean by as much as 16 Sv,…”

13) *P13237, lines 7-8: “in the southern part of the proto-North Atlantic Ocean”*

Reply: We have replaced “in the southern Atlantic” by “in the southern part of the proto-North Atlantic”. We did not added “Ocean” for consistency reasons as along the

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paper we refer to the North Atlantic in the mid-Cretaceous as the proto-North Atlantic.

14) *P13237, lines 20-21: Can you be more specific how biomarkers show evidence of lower euxinia?*

Reply: We changed the sentence to:

“However, low concentrations of isorenieratane in sediments suggest that euxinia in these northern areas was less common than in the southern proto-North Atlantic (van Bentum et al., 2012).”

15) *P13238, lines 8-10: Explain how the POC:P_{tot} ratio can be interpreted.*

Reply: We have now extended the sentence:

“However, ratios of particulate organic carbon to total phosphorus (POC/P_{TOT}) can be used as an indicator of bottom water redox conditions, with high ratios being indicative of more reducing conditions...”

16) *P13238, line 19: “inflow of nutrient from the Pacific”*

Reply: We have changed the sentence to:

“Besides riverine inputs, other inputs include the inflow of nutrients from the Pacific Ocean and Tethys gateway and release of P from shelf erosion during flooding.”

17) *P13240, lines 25-27: Constant to what?*

Reply: The sentence has been modified, replacing “i.e. surface water concentrations are assumed to be constant” by “surface water concentrations are assumed to be in equilibrium with the atmosphere and are therefore, not explicitly modeled.”

18) *P13241, lines 14-17: For which region 13% of primary production is valid?*

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Reply: We have changed the text to clarify this:

“In both the open and coastal ocean, 13 % of primary productivity is assumed to be exported from surface waters.”

19) *P13257, line 1: May add quick info on what E6 experiment is here to prevent the reader to look for the info in the table*

Reply: We assume the reviewer is referring to line 1 of P13252. We already include information on experiment E6 in the sentence, but have made the information more explicit:

“In experiment E6, such a combination of factors is assessed in an attempt to define a real scenario for OAE2. In this experiment, we assume a 3-fold increase in P input from rivers and increased erosive input of P, together amounting to $0.031 \text{ Tmol y}^{-1}$, and elevated SRP and lower oxygen concentrations in Pacific bottom waters (at 2.9 and $130 \mu\text{mol L}^{-1}$, respectively...”

20) *Table 1: Explain what you mean by “where available”*

Reply: In some cases, notably in the Western Interior, data from geological records could not be obtained because, for example, the interval of interest was not present in the core or the data of interest were not measured. We refer to this as “not available” in the table. We have now modified the caption:

“Mean sediment POC contents for each box, where observations have been recorded, and corresponding POC burial fluxes, rates of primary productivity and oxygen concentrations in bottom waters for pre-OAE2 conditions. The mean POC contents have been calculated from the observations shown in Fig. 1 and Table S1.”

21) *Table 1: Add description of the Box in addition to the labels W1-W7 to add clarity (Open ocean, South boundary ...)*

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Reply: The description of each box has been now added in Table 1.

22) *Figure 3: It would be useful to show also pre-OAE2 vertical flux of Topper et al. (2011) model.*

Reply: The vertical fluxes as deduced from the model of Topper et al. (2011) are listed in Table S2 in the supplementary material and are shown with symbols (blue and yellow circles) in Figure 3a. We think that showing an additional figure with the vertical fluxes of pre-OAE2 would not add significant information to our results. The regions dominated by upwelling or downwelling during pre-OAE2 and OAE2 are very similar. The major change is in the strength of the vertical fluxes. The vertical fluxes for pre-OAE2 conditions are less strong than during OAE2. This is relevant when calculating the initial conditions, but the pre-OAE2 water cycle does not have a direct impact on the steady state results during OAE2.

23) *Figure 3: What are the arrows for the middle of the open ocean box?*

Reply: The arrows in the middle of the central open ocean are not essential to the paper and were removed to avoid confusion

24) *Figure 4: Mention that the levels of P input relative to standard run are indicated in dashed white lines.*

Reply: The caption of figure 4 has been modified and now reads as follows:

“Oxygen concentrations versus riverine P input for a) Experiment E1 and b) Experiment E2. The basins of the model are W5 (southern coast), W2 (southern open ocean), W1 (central open ocean), W3 (Western Interior Seaway), W4 (northern coast), W6 (north-eastern coast), W7 (Tethys gateway) and i, b are the indexes for intermediate and bottom waters. The levels of P input are indicated relative to the standard run (dashed horizontal white lines, where for example, 10x indicates a P input that is 10-

fold higher than in the standard run). The colour bars below the x-axis indicate the oxygen conditions for each basin as deduced from observations for OAE2 (Fig. 1b) where dark red = euxinic/anoxic, orange = low oxygen/anoxic, blue=low oxygen/oxic, gray = uncertain. In b), the P levels corresponding to the SRP concentration of the modern Pacific bottom water and its doubling are indicated (dashed horizontal white lines)."

25) *Figure 6: x and y labels are not very well positioned. Maybe move River P input slightly higher?*

Reply: The labels of x and y have been repositioned.

26) *Say that the ocean circulation is reduced by x%*

Reply: We have made the change and the modified caption now reads:

"Sensitivity of oxygen concentrations in the bottom water of each box to changes in river input of phosphorus and ocean circulation (E5). The ocean circulation is reduced from 100 to 30 %. For further details, see text."

References

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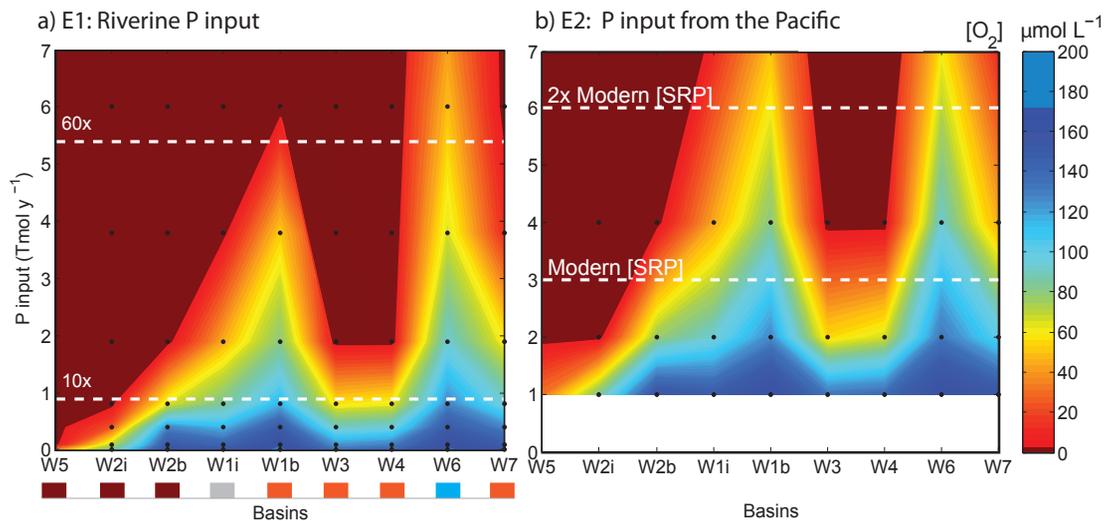


Fig. 1.

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