Review of “Exploring the mechanisms of Devonian oceanic anoxia: impact of ocean dynamics, palaeogeography and orbital forcing”. Justin Gérard et al. 2024, for Climate of the Past

1 Editor : Yannick Donnadieu

From my own reading, I found the paper to be both interesting and well-illustrated. However, due to the large number of simulations and the complexity of the processes you've addressed—ocean dynamics, oxygenation response to paleogeography, sensitivity to external factors, hysteresis phenomena, and orbital parameters—the paper can sometimes be difficult to follow. Despite this, your decision to report all of these simulations has yielded a strong outcome.

As you will see, the reviewers have raised several specific points that I would like you to address in full.

We thank the editor for his overall positive evaluation of the manuscript. We have indeed considered in detail all the comments of the two reviewers and prepared a point-by-point answer to each question or topic raised.

Questions about ocean dynamics and its variability persist in the current form of the paper. I strongly encourage you to delve deeper into this aspect to make the model's results more convincing.

Indeed, the questions of the reviewers have been stimulating and made us think further about the mechanisms behind the results we present. We have included supplementary information in the manuscript to improve the robustness of the results and have prepared two additional figures. One, we believe, can make its way through the final version of the paper (suggested new Figure 7) : it confirms the robustness of the ocean circulation response to successive increases in the CO_2 concentration. We have also clarified for Reviewer 2 the position of the fixed point in the 4x pCO_2 Scot390M experiment relative to those experiments where a limit cycle develops. We make the figure available in our answer to the reviewer, but suggest that having it in the final manuscript is less necessary.

For instance, a more in-depth analysis could explore the links between deep water formation areas and oxygen 3D distribution, as well as the sensitivity of these areas to continental configuration and climate.

Indeed, we rephrased explanations about the role of nutrient availability versus changes and solubility in the response of oxygen content to increases in pCO_2 and global average temperature. We also clarified the straightforward role of ocean depth on ventilation age, with the higher average depth in the Vérard (2019a) reconstruction leading to older average water masses.

Reviewer 2 asks for more information about the causal mechanisms of the changes in circulation when pCO_2 increases. This is a challenging question and we explain why. In a previous contribution (Gérard and Crucifix, Earth System Dynamics, 2024) we explored the value of off-line diagnostics for attributing causes to changes in circulation and we explained why there is no easy solution for disentangling haline and thermal contributions to the change in steady-state circulation state. The topic could deserve further exploration, perhaps using more models (through an inter-comparison project) but this is probably out of the scope of this first contribution on the effect of orbital forcing and continental configuration on the anoxic extent during the Devonian.

Keep in mind that a portion of atmospheric forcing in GENIE remains fixed or poorly resolved, such as the wind system and haline forcing of the meridional overturning circulation (MOC). Finally, while the multiple sensitivity tests to O_2, PO_4, and CO_2 add complexity to the paper, the question of their values remains. It's important to note that these variables are not independent of each other.

Absolutely ! This is precisely why we hope our article will stimulate further studies, ideally using additional models, to confirm or refute some of the scenarios we propose. A natural next step would be to conduct and analyze experiments incorporating more feedback mechanisms— i.e. in which more links between the different state variables are taken into account. Additionally, we have added several clarifications throughout the manuscript to support the chosen values for pO_2, pCO_2, and $[PO_4]$.

2 First reviewer : Anonymous Referee 1

This manuscript investigates Devonian OAEs by performing and analyzing systematic sensitivity experiments using the cGENIE Earth system model. The multiple sensitivity experiments are used to quantify the impact of continental configuration, ocean-atmosphere biogeochemistry, climate forcing and astronomical forcing on background oceanic circulation and oxygenation during the Devonian. I find that results of these simulation are interesting, providing new insights into the ocean anoxic events, the analyses of the results are basically sound, and the manuscript is well-organized, although I had some questions regarding the simulations and interpretation of results after reading through the paper.

We thank the reviewer for his relevant and constructive comments on the manuscript and for recognizing the value of our study.

Specific comments are listed below that may help further improve this manuscript :

1. Section 2.3 : It would be of much help if a table summarizing the key set-ups of the three sets of simulations could be provided in the manuscript.

The following table was added to the manuscript to improve clarity.

Set 1	Type	Period (Ma)	pCO_2	$[PO_4]$	pO_2	Eccentricity	Obliquity	Precession
	Scot	360; 365; 370; 375; 380; 385; 390; 395; 400; 405; 410; 415; 420	1	1	1	0	23°	0°
	Vera	370; 383; 393; 408; 420	1	1	1	0	23°	0°

Set 2	Type	Period (Ma)	pCO_2	$[PO_4]$	pO_2	Eccentricity	Obliquity	Precession
	Scot	370; 390; 420	1; 2; 4; 8; 16	1; 1.25; 1.5; 1.75; 2	0.4; 0.7; 1	0	23°	0°
	Vera	370; 393; 420	1; 2; 4; 8; 16	1; 1.25; 1.5; 1.75; 2	0.4; 0.7; 1	0	23°	0°

Set 3	Type	Period (Ma)	pCO_2	$[PO_4]$	pO_2	Eccentricity	Obliquity	Precession
	Scot	370	2	1.25	0.7	0; 0.06	21°; 25°	0°; 90°; 180°; 270°
	Scot	390	2	1.25	0.7	0; 0.03; 0.06	21°; 22°; 23°; 24°; 25°	0°; 45°; 90°; 135°; 180°; 225°; 270°; 315°
	Vera	393	2	1.25	0.7	0; 0.06	21°; 25°	0°; 90°; 180°; 270°

TABLE 1 - Experimental design. 'Type' indicates whether the continental configuration is based on Scotese and Wright (2018) or Vérard (2019a). pCO_2, $[PO_4]$, and pO_2 are expressed as multiples of preindustrial levels. When variables have multiple values, all possible combinations have been tested.

The text was modified accordingly to ensure proper referencing. The following sentence was added at the end of section 2.3 :

Line 166 : "Table 1 provides a schematic overview of the three experiment sets."

2. Lines 208-210 : The authors argue that for both reconstruction types, the Middle and Late Devonian exhibit a higher susceptibility to anoxia due to the broader OMZ extent associated with these periods. However, the OMZ extent reaches minimum after 405 Ma, according to

Figure 4. Could you explain why "Middle and Late Devonian" is used ? Otherwise, please revise the corresponding discussion.

To clarify the meaning of the sentence, the text was adapted in the following way :

Lines 216-219 : "For both reconstruction types, the Middle (roughly 394-379 Ma) and Late (roughly 379-360 Ma) Devonian exhibit a higher susceptibility of reaching an anoxic event due to the broader average OMZ extent associated with these periods, and this is consistent with the temporal distribution of observed anoxic events (see Fig. 22.13 in Becker et al., 2020)."

3. Figure 5a : The continental configuration for Vera393M is not consistent with that in Figure 2. For example, there is a passage at around (50S, 50W) in Figure 2, but there is continent at the same grids in Figure 5a.

This is due to the difference in depth. The following sentence was added to the caption of Fig. 5 to prevent any confusion :

"The continental configuration in (a) is valid at 1.5 km depth. Grid cells representing land at this depth are shaded gray. Hence, it differs slightly from that in Fig. 2, which represents surface bathymetry."

4. Figure 6 : Could you explain why 4 times pCO_2 is used here, instead of 2 times or 1 time as control ? Also, 0.4 times pO_2 and 1.5 times PO_4 are used in Figures 6, 7, 8, but why 0.7 times pO_2 and 1.25 and 1.75 times PO_4 are chosen for Figures 9a and 9b ? It would be helpful if the authors could add some clarification on how the values are chosen for different experiments.

To better explain why 4 times pCO_2 is used in Fig.6, the following sentence was added to the caption :

"This pCO_2 was chosen to avoid interference from limit cycles, which only occur at 1 and 2× pCO_2."

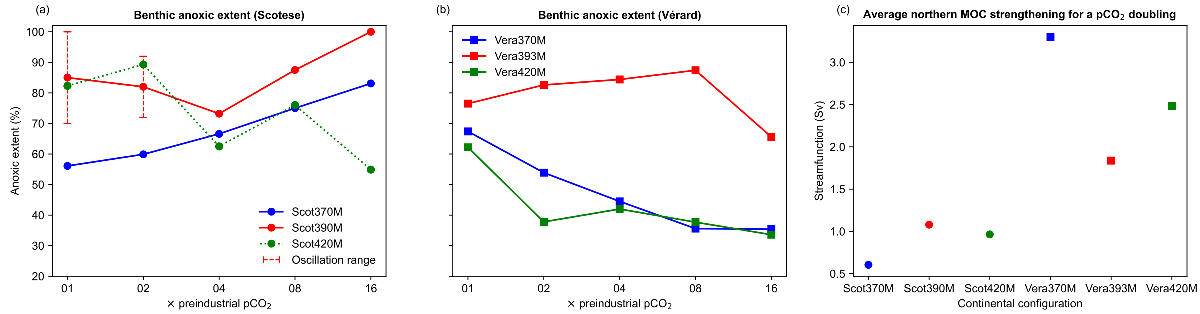
Similarly, to better explain why specific PO_4 and pO_2 values are used in Fig. 9a and b, the following sentence was added to the caption :

"These pO_2 and $[PO_4]$ values were selected to illustrate the full extent of the influence of the limit cycles on the system."

5. Lines 251-252 : I am a little curious whether it's robust that the northern overturning circulation is always strengthened with each doubling of pCO_2. It would be more convincing if related figures could be provided in the supplementary materials.

The figure below is a modified version of Fig. 7, where we added panel c. This panel illustrates the average strengthening of northern MOC for a pCO_2 doubling for different continental setups. It shows that while MOC strengthening is always positive, it can heavily be influenced by continental configuration, generally being greater for the Vérard (2019a) configuration than for the Scotese and Wright (2018) configuration. The northern MOC consistently strengthens with each pCO_2 doubling, a pattern observed across all tested continental configurations using cGENIE. However, we acknowledge that different models may yield varying results.

This new Fig. 7 was added to the manuscript with proper referencing and caption changes.



Caption : "(c) Average northern Meridional Overturning Circulation (MOC) strengthening following a pCO_2 doubling using the continental reconstructions of (a) and (b)."

Lines 270-272 : "For the reconstructions of Scotese and Wright (2018), the alterations of the overturning cell are small, reaching an average strengthening of 1 Sv across the entire ocean, while it often reaches 2 to 3 Sv with those from Vérard (2019a) (see Fig. 7c)."

6. Figure 8 caption : Should it be anomaly between 4 and 2 times pCO_2 for (c), and between 2 and 1 times pCO_2 for (f) ?

Well spotted. The caption of Fig. 8 has been modified to correct the mistake :

"(c) Benthic $[O_2]$ anomaly between 4 and $2\times pCO_2$ for Scot370M. (f) Benthic $[O_2]$ anomaly between 2 and $1\times pCO_2$ for Vera370M."

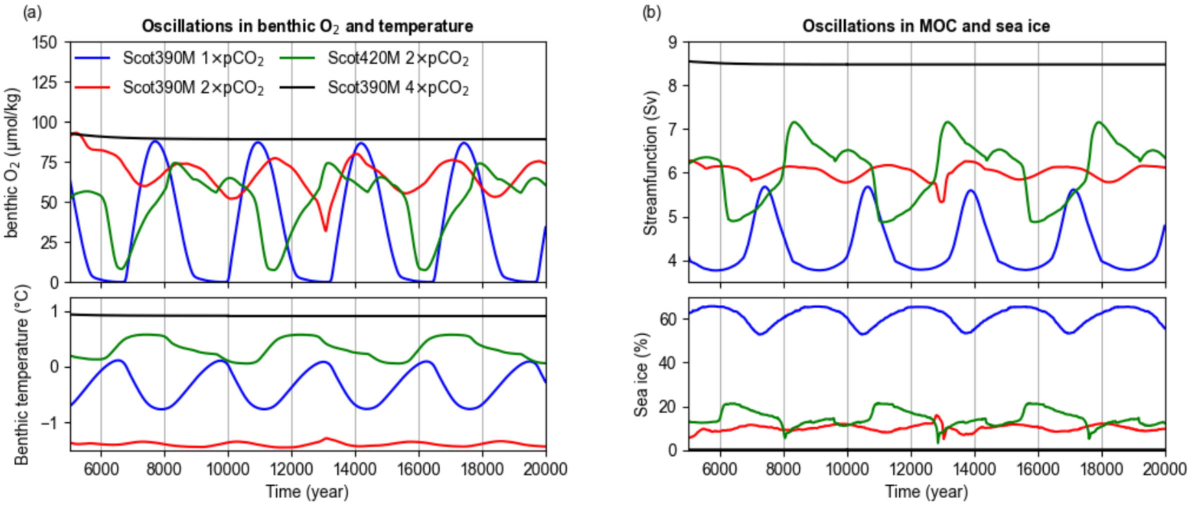
7. Lines 264-270 : Could you explain why the active circulation cell does not efficiently ventilate the anoxic areas left in the benthic ocean when the nutrient availability is relatively low ?

To clarify this phenomenon, the manuscript was revised as follows :

Lines 273-280 : "In some cases, effects related to nutrient availability may determine the total effect on oxygen content. For example, in Vera370M, anoxia generally decreases when pCO_2 increases, because of the increase in circulation. In some simulations, though, we see the opposite (see Fig. 8e). This occurs at low $[PO_4]$ and when the ocean is already well-oxygenated. As $[PO_4]$ decreases, the benthic anoxic boundary shifts southward (see Fig. 8c) and may reach areas less affected by MOC strengthening. In these simulations, even though circulation strengthens in response to rising temperatures, the active circulation cell does not efficiently ventilate the anoxic areas left in the benthic ocean. Consequently, the main cause of $[O_2]$ change is solubility loss, leading to a subsequent decrease in $[O_2]$. The same reasoning can be applied to explain the small mismatch between Vera370M and Vera420M (blue and green curves in Fig. 7b) when increasing from 2 to $4\times pCO_2$."

8. Lines 288-291 : Could you show the results of Scot390M 4 times pCO_2 in Figures 9a and 9b, to better explain the trend observed in Figure 7a ?

Here is a version of Figures 9a and 9b with the Scot390M 4x pCO_2 simulation in black. The primary purpose of these figures is to illustrate the impact of limit cycles on different system quantities. While adding this simulation allows for a slightly better understanding of the results displayed in Fig. 7a (although not straightforward), we believe that the absence of a limit cycle at 4x pCO_2 reduces the relevance of including this version of the figure in the manuscript. Hence, we advocate for leaving Fig. 9 as it is.


(a)
Oscillations in benthic O$_2$ and temperature
Scot390M 1×pCO$_2$
Scot390M 2×pCO$_2$
Scot420M 2×pCO$_2$
Scot390M 4×pCO$_2$
benthic O$_2$ (µmol/kg)
Benthic temperature (°C)
Time (year)
(b)
Oscillations in MOC and sea ice
Streamfunction (Sv)
Sea ice (%)
Time (year)

3 First reviewer : Anonymous Referee 2

Gerard et al. use the Earth system model of intermediate complexity with active biogeochemical cycling, cGENIE, to better understand the mechanisms underlying enhanced ocean anoxia during the Devonian. The sensitivity experiments with cGENIE explore the relative importance of paleogeography, orbital configuration, global mean oceanic PO_4 concentration and atmospheric pO_2, and atmospheric pCO_2 in preconditioning Devonian ocean anoxia. Of these factors considered, Devonian paleogeography plays a leading role in promoting ocean anoxia by directly influencing ocean circulation, which causes an expansion in oxygen depleted zones. Paleogeography also modulates the impacts of orbital configuration, oceanic PO_4 concentration, atmospheric pO_2, and atmospheric pCO_2. An increase in oceanic PO_4 and decrease in atmospheric pO_2 exacerbate ocean anoxia. Changes in pCO_2 lead to large reorganizations of ocean dynamics, and potentially provide an explanation for the prolonged duration of some ocean anoxic events. Also, changes in orbital configuration, particularly obliquity, influence ocean oxygen variability by altering ocean circulation and oxygen solubility. Gerard et al. have produced a novel set of simulations that contribute to our understanding of the drivers of Devonian ocean anoxic events, the results are well organized/communicated, and the model limitations are clearly stated. I only have minor comments and questions that are explained in more detail below.

We are grateful to the reviewer for their encouraging feedback and insightful comments on our study.

Main comments :

Section 3.1 (Lines 169-175) : How does the number and extent of deepwater formation zones differ between the Scotese and Wright (2018) and Verard (2019a) paleogeographies ? Decreased deepwater formation in Verard could also lead to increased global mean ventilation age. I am wondering if the number and extent of deepwater formation zones is similar between the Scotese and Wright (2018) and Verard (2019a) paleogeographies and therefore it is clear that seafloor depth is the most important factor for global mean ventilation age ?

To better justify that ocean depth is the primary factor influencing the ventilation age of the benthic ocean, we have adapted the text in the following way :

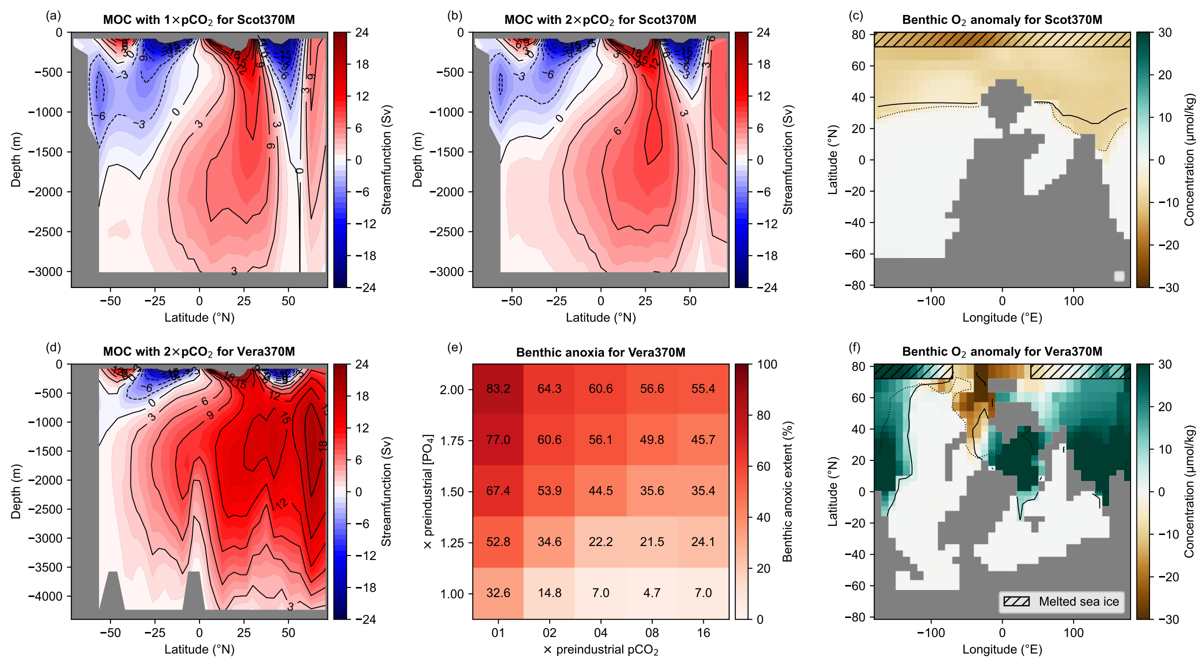
Lines 173-183 : "Simulations using reconstructions of Vérard (2019a) generally present higher ventilation ages because the ocean floor is deeper, increasing the time needed by water masses to reach these depths. In our experimental design, seafloor depth emerges as the primary factor influencing average ventilation age, as no significant differences were observed in the number or extent of deep water formation regions between the Scotese and Wright (2018) and Vérard (2019a) reconstructions. Additionally, when the ocean floor depth was artificially reduced in the Vérard (2019a) reconstruction, to align with that of Scotese and Wright (2018), the average ventilation age decreased, reaching similar values to those observed with the Scotese and Wright (2018) reconstruction. Figures 3a and b show that the global average dissolved $[O_2]$ and ventilation age evolve in opposite directions ($r^2 = 0.91$ with p-value $= 4.3\times10^{-7}$ and $r^2 = 0.93$ with p-value $= 0.008$ for the set of reconstructions from Scotese and Wright (2018) and Vérard (2019a), respectively). This suggests that the variations in oxygen concentration are primarily explained by changes in ventilation, caused by modifications in ocean circulation dynamics induced by the prescribed differences in continental configuration."

Section 3.2.2 : Can you explain how this seesaw phenomenon relates to a potentially different surface temperature and salinity response in each hemisphere ? How are these temperature and salinity changes impacted by the melting sea ice, which then impact ventilation ?

It is challenging to fully address these points as our simulations represent an equilibrium state, and we prefer to avoid speculative conclusions. In past work (e.g. Gérard and Crucifix 2024), we show that even a detailed analysis of the geostrophic components of equilibrium simulations does not allow for proper identification of the causes of circulation changes. Therefore, separating the changes that are attributable to the seesaw effect from those of a different effect is non-straightforward with the material at hand. We suspect that sea ice does not play a significant role, as its presence is minimal and vanishes completely from 4x pCO_2 and higher scenarios. The seesaw phenomenon might instead be more closely related to the bathymetry, which helps structure the ocean circulation. Furthermore, continental configuration likely plays a central role in shaping the differential temperature and salinity responses between hemispheres. While the question of the reviewer is interesting, the explanation we offer here remains speculative and providing a definitive answer might be a bit out of the scope of the present study because our experimental sign is not suited to tackle such a fuller investigation.

Section 3.2.2 (Lines 276-277) : Should there be a hatched area for melted sea ice in Figure 8c ?

Fig. 8 was modified to correct this oversight. Here is the adapted version of Fig. 8 :



Minor comments :

Line 56 : Should “sensibility” be replaced with “sensitivity” ?

The manuscript was modified to correct this mistake :

Line 55-56 : “To meet our general objective, we conduct various sensitivity analyses around those parameters.”

Line 32 : Break to a new paragraph at "Extensive".

We have taken the reviewer's advice into account and introduced a new paragraph beginning with 'Extensive'.

Line 135-136 : I would cite Fig. 1 here because from Fig. 1 caption alone, it is not clear why the surface albedo is hemispherically symmetric.

The text was adapted to avoid any confusion :

Line 136 : "The albedo profile depends on the latitude only (see Fig. 1)."

Line 157-159 : What justification did you use to choose these ranges in pCO_2, PO_4, and pO_2 ?

A justification was added for the chosen range of parameters at the end of section 2.3 :

Line 157-163 : "We used a combination of atmospheric pCO_2, with 1, 2, 4, 8 and 16 times the preindustrial value, global mean oceanic [PO_4], with 1, 1.25, 1.5, 1.75 and 2 times the modern concentration and atmospheric pO_2, with 0.4, 0.7 and 1 time the preindustrial value. Values for pCO_2 and pO_2 were selected to capture a significant portion of the range and uncertainties associated with these parameters throughout the Devonian, with pCO_2 levels from Foster et al. (2017) and Brugger et al. (2018), and pO_2 levels based on Cannell et al. (2022) ; the range for [PO_4] concentrations was chosen following similar studies on ocean anoxic events using cGENIE (Monteiro et al., 2012 and Hülse et al.,2021)."

Cannell, A., Blamey, N., Brand, U., Escapa, I., & Large, R. (2022). A revised sedimentary pyrite proxy for atmospheric oxygen in the Paleozoic : Evaluation for the Silurian-Devonian-Carboniferous period and the relationship of the results to the observed biosphere record. Earth-Science Reviews, 231, 104062.

Monteiro, F. M., Pancost, R. D., Ridgwell, A., & Donnadieu, Y. (2012). Nutrients as the dominant control on the spread of anoxia and euxinia across the Cenomanian-Turonian oceanic anoxic event (OAE2) : Model-data comparison. Paleoceanography, 27(4).

Line 226 : Replace period with a space

The period has been replaced by a space.

Figure 5 caption : Please indicate what lines labeled A and H represent. An outline of anoxic and hypoxic conditions ?

The following sentence was added to Fig. 5 caption to improve clarity :

"The A and H lines respectively outline the boundaries of the anoxic and hypoxic regions, with thresholds set at 6.5 and 62.5 µmol/kg (after Sarr et al., 2022)."