Reviewer 2

We would like to thank Reviewer 2 for their insightful and helpful review. We have replicated the Reviewer's comments below in blue and italics. Our responses to each of the comments are in black and changes to the text in the manuscript are in red and bold. Thank you for your time and expertise!

The study by Duboc et al. investigated ocean oxygenation during the MIS 5e and MIS9e based on ACCESS-ESM1.5. The topic fits the CP, but the organization of the manuscript needs to improve.

Major comments:

1. *In the Introduction section, the authors provide reconstructed ocean oxygenation in the past climate using considerable length, and I think this paragraph can be summarized more briefly. Moreover, as this manuscript focused on the modeling, I recommend providing some key points on research progress on the numerical modeling. In addition, I suggest adding a paragraph at the end of this section by giving the organization of this manuscript.*

To the authors' knowledge, this is the first study modelling ocean oxygen conditions for recent interglacials. It is therefore not possible to provide more background on other modelling studies and discuss research progress on numerical modelling of oxygen during interglacials. We therefore decided not to shorten the paragraph in the introduction that discusses oxygenation during interglacials based on proxy reconstructions.

We have added following paragraph to the end of Section 1:

"This manuscript is structured as follows. Section 2 describes the model, the experimental setup and the time series for each of the analyzed experiments. Section 3 first analyses changes in large-scale circulation patterns and oxygenation and then focuses on changes in the Mediterranean Sea. In Section 4 we discuss uncertainties and situate our results within a broader context. Section 5 summarizes the main results."

2. *Lines 47-53: I feel confused about this paragraph. Why do you separate the Mediterranean Sea individually? If necessary, please provide transition sentences.*

We agree that a better transition was needed here and have changed the sentence to:

"One region with notably large changes in past ocean oxygen concentrations is the semi-enclosed Mediterranean Sea, where there is evidence of intervals with severe anoxia during past interglacials (Sachs and Repeta, 1999; Rohling et al., 2015; Rush et al., 2019). These intervals are characterised by…"

3. *In Section 2, the authors provide 1000~2000 model-year simulations in this study. In Figure A2, I don't think the simulated conditions reaching quasi-equilibrium. It is obvious that the global mean O_2 concentration, mean O_2 concentration in the Mediterranean Sea, and AABW mean O_2 still show a decreasing trend. Indeed, the deep ocean circulation generally needs more than 4000 model-year integration to reach quasi-equilibrium. I am wondering whether this imbalance may have an impact on your results.*

There is indeed still a small drift in O_2 in the global mean and in the Mediterranean Sea. Please see below zonal mean O_2 concentration drifts (shown here as anomalies between the last two 250-year averages).

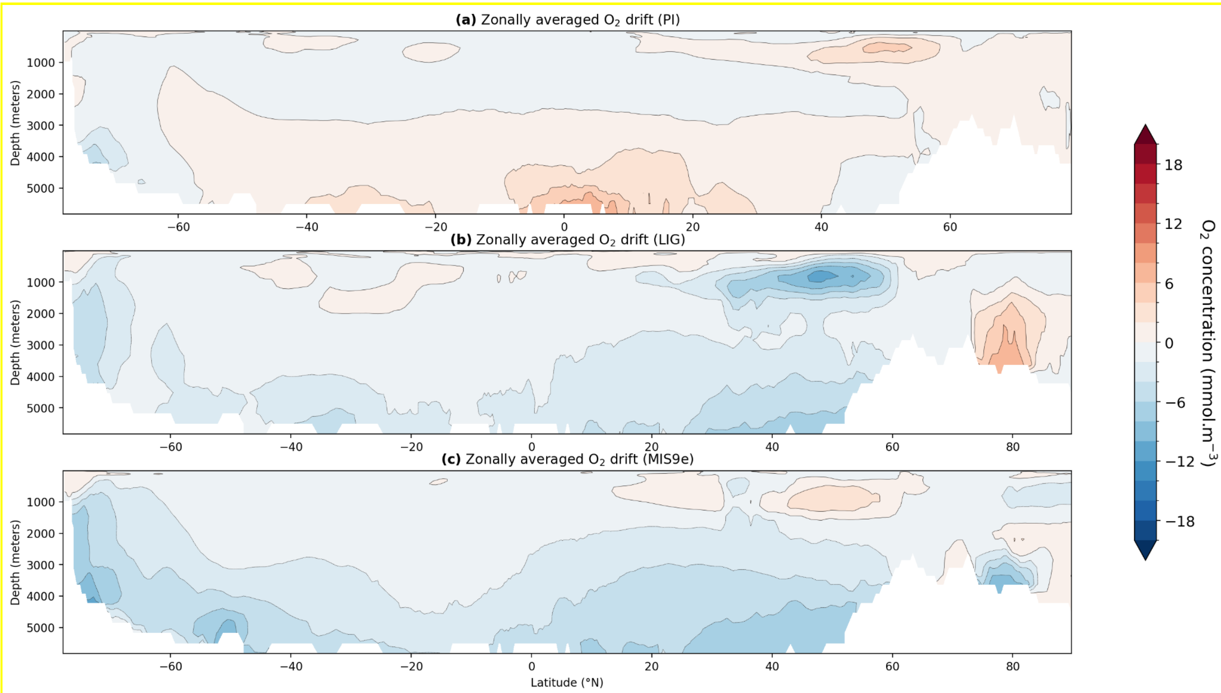

Figure R2.1: Zonal-mean oxygen concentration anomalies (250-year averages). 250 last years of simulation minus 250 previous years.

We have now moved Figure A2 to the main text (new Figure 1) and discussed this throughout the manuscript:

Methods:

"Dissolved oxygen is a tracer with very long equilibration times. Figure 1 shows time series of dissolved oxygen for the three simulations analysed in this study. While oxygen concentrations have reached quasi-equilibrium for North Atlantic Deep Water (NADW), in the intermediate waters of the North Pacific, and in Antarctic Bottom Water south of 35ºS in all runs, there is still a slight drift in global mean dissolved oxygen in our LIG and MIS 9e simulations and a more substantial drift in the Mediterranean Sea."

Results:

"It should be noted that oxygen concentrations in the deep waters in the Ionian Sea are still drifting in our simulations and might reach suboxic values if integrated for longer."

"It should be noted that oxygen levels in the Mediterranean Sea are still drifting in both simulations and that the equilibrium values are lower than what is presented here."

Discussion:

"In addition, note that Mediterranean oxygen content is still drifting in our LIG and MIS 9e runs. As a result, MIS 9e could reach similar oxygen loss as LIG on a longer timescale (Figure 1)."

Conclusions:

"Dissolved oxygen concentrations are still drifting in both simulations, even after integration times of well over 1,500 years."

"Oceanic oxygen takes centuries to adjust, and we currently lack computer power to run high-resolution models for the timescales needed for initialisation and equilibrium responses."

4. *In Section 3.1, the authors provide oxygenation changes in AABW, NADW, NPIW, and OMZ. Why do you choose these water/regions for analysis? Any opinions on other water masses? At least, the authors should introduce the importance of these water masses at the beginning of this section.*

We have added the following paragraph to the end of Section 3.1.:

"The next two subsections analyze changes in the main large-scale bottom and deep water masses, AABW and NADW. We also see significant changes in the oxygenation of North Pacific Intermediate Water, which are described in Section 3.1.3. Changes in low oxygen zones can have a large impact on marine life and biogeochemical cycles. We therefore analyze changes in the simulated Oxygen Minimum Zones in Section 3.1.4."

5. *In Section 3.1.1, authors declare changes in AOU, export production, and remineralization rates during the MIS 5e and MIS 9e. However, readers may feel confused about how these factors influence ocean oxygenation, because not all readers are familiar with these words. I suggest adding some illustrations on the definition and impact of AOU, export production and remineralization rates.*

We apologize for the omission. Following paragraph has been added to the end of Section 2:

"In Section 3 we partition changes in dissolved oxygen into two components, changes in the saturated concentration of oxygen O_2^{sat} and changes in Apparent Oxygen Utilisation (AOU). AOU estimates the oxygen consumed during respiration and can be calculated as the difference of dissolved oxygen concentration (O_2) and O_2^{sat}:

$$AOU = O_2^{sat}(T, S) - O_2 \qquad (1)$$

where T is the potential temperature and S salinity. Changes in AOU are therefore a combination of changes in circulation (with sluggish water masses tending to have higher AOU), and changes in remineralisation rates, which depend on the vertical export of organic matter (export production) and temperature. Please note that the here used metric AOU assumes that dissolved oxygen in surface waters is in equilibrium with the atmosphere, which might lead to an overestimation of the True Oxygen Utilisation (TOU) (Duteil et al., 2013)."

6. *Following comment #4, in Section 3.1.1, the authors declare changes in dissolved oxygen concentrations in AABW are linked with changes in ocean circulations, with the increase in export production and remineralization rates. Do changes in ocean circulation impact export production and remineralization rates? If so, how do you distinguish their exact contribution to the ocean oxygen concentrations? Moreover, ocean circulation, export production, and remineralization rates are linked with increased temperature. Therefore, I speculate that changes in thermal structures in the ocean induced by solar insolation anomalies may drive variations in ocean oxygenation ultimately. Same comments on Section 3.1.2-3.1.4.*

Unfortunately, we cannot distinguish between the contribution of circulation changes, export production and remineralization rates to changes in oxygen concentrations within this modelling frame.

We can calculate saturated O_2, which depends on water temperature and salinity. The difference between in situ O_2 and saturated O_2 then gives us an indication of O_2 consumption.

O_2 consumption, or apparent oxygen utilization, for a particular water parcel will depend on the history of this water parcel since it has last "seen" the atmosphere. It will be the integral of remineralisation rates during its journey. When we compare two simulations, changes in remineralisation rates can be therefore be due to

(a) changes in the availability of organic matter to remineralise on the pathway of this water parcel (i.e. changes in export production),

(b) changes in temperature on the pathway of this water parcel (i.e. remineralisation will increase with higher temperatures due to higher metabolic rates), and, most importantly,

(c) changes in circulation (i.e., if circulation weakens and residence times increase, the integral of remineralisation rates since last contact with the atmosphere will increase).

In addition, ocean circulation changes will of course also be influenced by temperature changes, and export production will also depend on nutrient availability (and temperature), which depends on ocean circulation.

7. *Following comment #1, in Section 3.2, I am curious about the uniqueness of the Mediterranean Sea. I suggest adding some sentences in the Introduction and Section 3 that illustrate the necessity of separating the results of the Mediterranean Sea individually, e.g. its large region, substantial drift in oxygenation…*

We have rephrased the sentence introducing the Mediterranean Sea in the Introduction as follows:

"One region with notably large changes in past ocean oxygen concentrations is the semi-enclosed Mediterranean Sea, where there is evidence of intervals with severe anoxia during past interglacials (Sachs and Repeta, 1999; Rohling et al., 2015; Rush et al., 2019). These intervals are characterised by…"

We added following paragraph at the beginning of Section 3.2.:

"The Mediterranean Sea is a semi-enclosed sea which is linked to the Atlantic Ocean via the relatively narrow and shallow (< 900 m) Strait of Gibraltar. Changes in large-scale circulation therefore impact the Mediterranean Sea only moderately, although the opposite is not true, as the Mediterranean outflow impacts the large-scale circulation in the Atlantic Ocean (Barbosa Aguiar et al. , 2015). There have been numerous time intervals during past interglacials when some regions of the Mediterranean Sea became anoxic, prompting us to analyse changes in simulated dissolved O_2 in the Mediterranean Sea in this section."

8. *Lines 246-250. How is this conclusion proposed? Indeed, although Earth's orbit and greenhouse gases are the main external forcings in MIS 5e and MIS 9e. However, changes in incoming solar insolation are the dominant external forcings, with its radiative forcing quite larger than the*

greenhouse gases. I speculate that the less oxygenated conditions during MIS 5e and MIS 9e may be tied to changes in solar insolation driven by Earth's orbit compared with the PI, rather than their differences in greenhouse gases.

Yes, the Reviewer is correct. To make the conclusion clearer, we added the words in red:

"**The large-scale ocean circulation patterns, including AABW, NADW and the ventilation of the North Pacific Ocean are therefore very sensitive to the latitudinal and seasonal distribution of incoming solar radiation in the ACCESS ESM1.5, and less sensitive to changes in greenhouse gas concentrations within the range of these three interglacials. The insolation anomalies are indeed quite similar for LIG and MIS 9e (Figure A1), while the greenhouse gas forcing is highest for MIS 9e, lowest for LIG, with PI being in the middle (Table 1).**"

9. *In the Abstract and Introduction sections, the authors illustrated that the MIS 5e and MIS 9e may provide a reference for ocean oxygenation in a warmer world. I want to see more discussions on how the less oxygenated conditions during MIS 5e and MIS 9e may provide insight for reducing uncertainties in future ocean deoxygenation.*

Following paragraph has been added to Section 4:

"Our study shows that even relatively small changes in boundary conditions can lead to large changes in ocean circulation, upwelling systems, export production, and ocean oxygenation. While our results cannot directly inform on future changes in ocean oxygenation, there might be some similarities. Ocean temperatures and ocean stratification are projected to continue to increase until atmospheric CO_2 concentrations finally plateau. Current ocean deoxygenation is therefore not easily reversible and will persist for centuries (Oschlies, 2021). There will be physiological and morphological impacts on organisms, including reduced growth for a vast range of taxonomic groups (Sampaio et al., 2021). Exposure to low oxygen conditions has also been associated with a delay when fish produce eggs, a reduction of the number of eggs fish produce and blindness (Landry et al., 2007; McCormick andLevin, 2077). The metabolic demand of oxygen increases with water temperature, and when combined with deoxygenation, this can lead to respiratory distress, followed by respiratory failure and death (Clarke et al., 2021). Over 50 mass mortality events due to hypoxia have been recorded in the tropics to date (Altieri et al., 2017). The consequences of deoxygenation for fisheries and the world's future food supply could thus be serious (Oschlies et al., 2018; Rose et al., 2019)."

Minor comments:

1. *Line 160, adding abbreviation (OMZ).*

   The abbreviation was added.

2. *Fig. 2, adding boxes indicating the region of AABW, NADW….*

We decided not to add these boxes, as this visualisation is standard in oceanography and boxes would reduce the visibility of the plots.

3. *Adding significant test for anomalies between MIS 5e and PI, MIS 9e and PI, and MIS 9e and MIS 5e.*

We would like to thank the Reviewer for this suggestion (also mentioned by Reviewer 1). We have now performed significance tests on all results. All figures that show anomalies now clearly indicate regions that are not statistically significant.

4. *Enlarging the titles in the figures, they are too small.*

This comment was mirrored by Reviewers 1 and 3. We have now changed all the figures. In particular, we have:

- Removed the titles of the subplots;
- Made the legend colour bars thinner where appropriate;
- Increased the font size for all remaining text in the figures;
- Reduced the white space between subpanels where possible.

Thank you again for the helpful review that helped us improve the paper.