

We thank the reviewer for their helpful and constructive comments. The comments are listed below in black, with our response to each in blue. We hope that you find the improved manuscript suitable for publication.

In this study, the authors use ship-based observations along a repeat section in the North Atlantic to disentangle the mechanisms driving ocean deoxygenation, i.e., solubility and remineralization changes, and changes in ocean circulation. By using a matrix of equations, the authors have decomposed the changes in oxygen, DIC and temperature over the past nearly three decades. This study shows that the deoxygenation in upper 2000m is dominated by an increase in remineralisation via circulation changes, and the increasing temperature is becoming a more and more important mechanism to drive the upper ocean oxygen loss. The main conclusion is straight forward and the manuscript is generally well written.

We have some general comments here:

1. The writing structure of the results part is a bit fragmentary, especially in section 3.2. I encourage the authors to regroup the current paragraphs (sentences).

Section 3.2 has been edited to improve the flow of the text.

2. It is a good study to show how the interior ocean deoxygenized, through multiple GOSHIP transects, but we have a general impression that this study is a bit incomplete. For example, (1) the authors didn't explain well how they deal with the potential bias between the several ship tracks, which might result from the different measurement methods, different seasons of the ship track undertaken; (2) there is a clear different pattern of the oxygen changes between the west and east parts of the transect. It's not clear why the authors didn't discuss this signal, but instead, they took the average of the whole section. Please refer to the more specific comments below.

Using the GLODAP data product rather than raw bottle measurements resolves much of this potential bias. Extensive quality control has already been undertaken to produce the GLODAP dataset, and adjustments applied when required. The adjustments are applied in order to remove the biases that arise due to differences and errors in measurement and calibration techniques. We have also consulted with the GLODAP team, and there were no major changes in methods used for measuring oxygen or DIC data between these cruises. All the data used in this analysis was collected and analyzed using standard operating procedures, outlined in the GO-SHIP manuals (Langdon, C., 2010 and Dickson et al., 2007). More information about the GLODAP product has now been added to the manuscript:

"The GLODAP data product has undergone extensive quality control, with adjustments applied when required, in order to remove any biases between cruises (Olsen et al., 2016)." (Lines 67-68)

"The data collected during these cruises were collected and analysed using standard operating procedures as outlined in the GO-SHIP manuals (Langdon et al., 2010, Dickson et al., 2007)." (Table A1 caption)

While there are differences between the east and west of the section, we find it more logical to focus on the central region of the section, where the most robust deoxygenation trends occur, and are not influenced by the extreme localised values observed in the most westerly

and easterly parts of the section. If we average the changes in oxygen over the eastern and western halves of the section, there would still be significant regional differences within the halves, particularly due to the influence of Mediterranean water in the east and boundary currents and Florida Strait in the West. Therefore, while it would be interesting to use the same method to look at more localised changes, we believe it is sensible to first focus on the more robust changes in the average of the central region.

To make this consistent throughout the manuscript, we have instead included the average temperature, DIC and oxygen profiles for the whole of the central region of A05 in Fig. 1, so they are averaged over the same region as in Fig. 5. We have also included the mean properties of the section in Fig. 1e-g so spatial variability is still included. We have included further discussion about why we choose to average over this section:

“we focus on the region between 30–70°W (black box in Fig. 1a). This allows us to focus on the central region that has more robust trends in the upper 1000 m, with clear deoxygenation over time, while removing the impact of regional oxygen increases occurring in the eastern and western boundaries of the section.” (Lines 212-215)

3. The title suggests that remineralization is the primary cause of oxygen change, but the abstract and the main text indicate that it is actually circulation changes that lead to a change in the spatial pattern of remineralization. Please reword the title to make this clearer

Thank you for the suggestion. Since further work is required to be sure that circulation driving the remineralisation change, and we can only speculate that this is the case with this method, we have kept the title the same. However, we have added extra information throughout the manuscript to explain the different potential drivers of the change in remineralisation, and why we believe circulation to be the most likely driver.

Overall, agreements between treatments of independent ship transects and justification of different signal between west and east seem to be robust. The manuscript is also readable and well organized. However, before publication, several methodological problems need to be fixed (declared), discussions need to be refocused, and some typos and visualization issues need to be fixed.

Method.2.1 We think the important information about how these GO-SHIP transects deal with the samples is missing. Were there any changes in methodology over the three decade time period? Although the authors listed the expocode in Table A1, we suggest adding more information in the method section, such as a simple, summarized protocol (consistent part for all the transects) and a transparent reminder of any potential biases and differences from transect to transect.

The GLODAP data product already takes into account any changes in methodology, by applying adjustments to the cruise data if required to correct any biases. However, we have consulted with the GLODAP team, and have been told that there were no major changes in the methods used for sampling and processing oxygen and DIC data between these cruises. All the data used was collected and analyzed using standard operating procedures, as outlined in the GO-SHIP manuals (Langdon, C., 2010 and Dickson et al., 2007). A line has now been added in the caption of Table A1 to state this, and the manuals cited.

Line 83: 'However, the water mass properties we are interested in change more slowly, and so are resolved by the ~5-year frequency.' Do the authors have any reference for this?

This sentence has now been rephrased to explain that we are interested in those longer-term changes that are resolved by the frequency of cruise:

"However, we are interested in the longer-term changes in water mass properties, which are resolved by the ~5 year frequency."

Figure 1.

I would put the profiles from the west above (i.e., b-d) the profiles from the east (i.e., e-g). Since we read from left to right, this is how I would expect the outline of the figure.

The profiles for the east and west of the section have now been removed. Instead, we show the profiles averaged over the central part of the A05 section, to match the profiles in Fig. 4. However, the temporal average of temperature, oxygen and DIC for the entire section has now also been included, so the spatial variability can be seen across the section.

And we would suggest the authors use another way to plot the ship-transects in the map (1a). I understand that the authors have stated they interpolated the six transects to a uniform shape, but a black line with a part stack on the continent is not very informative. Perhaps showing the location of the casts would be helpful as a piece of information to aid the readers in understanding the transects.

Thank you for the suggestion, the line on the map has now been replaced by markers showing the individual CTD casts of the A05 cruise in 1992. As it is difficult to display the stations from every year, due to many of them overlapping, the 1992 station locations are shown since all changes in oxygen are calculated as the change from 1992.

What's the purpose of separating into two sections (west/east)? It seems like the whole study discussed the transect as a whole (mainly focused on 30-70W).

The authors switch between using the 30–70W average and the whole transect in Figures 1 – 5. If there are important differences between the west and east section, they should be presented and discussed separately and if there are no differences, then this should be stated up front and thereafter only the 30-70W averages shown and discussed.

Thank you for the suggestion. We agree that it was not consistent to split the section into east and west in Fig. 1 when we do not separately analyse the two halves of the section. Instead, we have changed Fig 1 to have only the averaged profiles across the whole of the A05 section.

Figure 2. Since this figure is discussed before the acronyms are explained in the main text, I think it would help the reader to explain what e, d, rd, and rem stand for in the figure caption. Or maybe include the acronyms at the beginning of section 2.2.

These acronyms have now been defined in the caption of Fig. 2.

Lines 100 – 102: the text preceding the equations goes through them in order of temperature, DIC, and O₂. I would suggest listing the equations in that order for ease of reading. Equation 10 has two equations; please numerate these separately.

The order of equations has now been changed, and Equation 10 has been split into two separate equations.

Section 2.6: Would a different Redfield Ratio change the result? I see this is discussed later, so I suggest bringing this up at this point.

This is included in the discussion, but the following has now been included earlier in Section 2.6: “While variation in the Redfield ratio was tested, even changing the value by as much as 50% has little impact on the overall findings (Fig. B1).” (Lines 181-182)

Line 211 & 252-253: could the authors please also report p values?

p values have now been added for all calculations of r^2 .

Line 248: Suggest rephrasing “lower depths” to deeper depths, as I assume this is what was meant? Lower is ambiguous in this context.

This has now been changed to deeper depths.

Line 236. Steadily increasing trend? Over time?

This has been changed to “steadily increasing trend over time”. (Line 262).

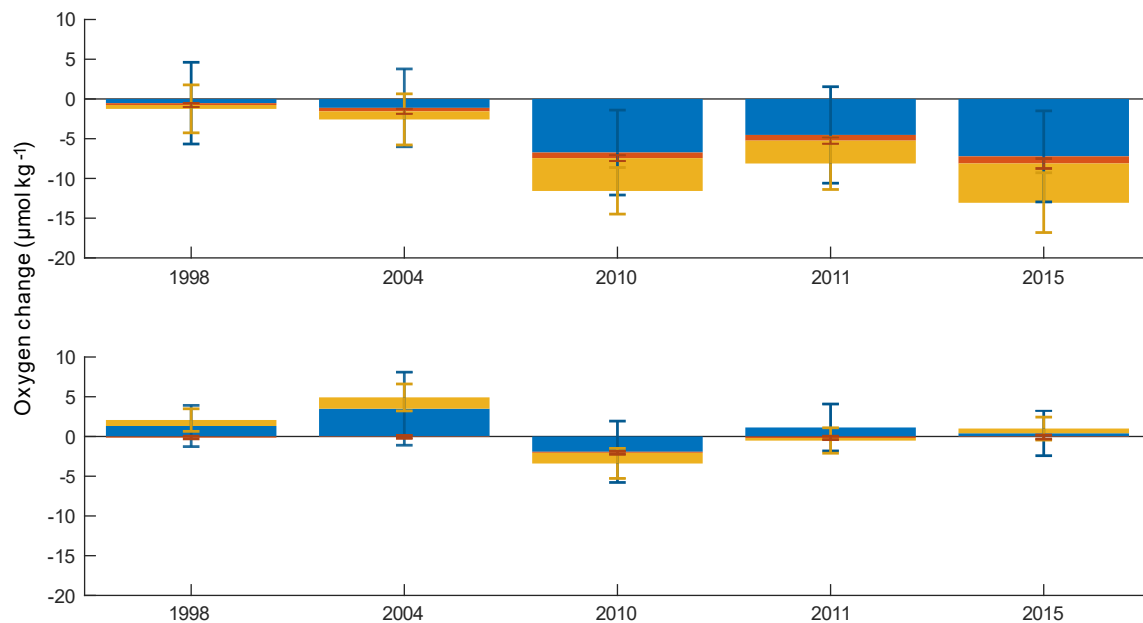
Line 240. Could the authors please refer to a plot or table?

Fig. 5m has now been referenced. (Line 244)

Figure 6. Sometimes we found it hard to see the error bars since they overlap, and the straight line between each dot makes it look like a linear trend, although it's not. Thus, we suggest using a better way to visualize this figure, for example a bar chart with stacked components.

We have tried to reproduce this figure in a number of different ways, including as a stacked bar chart (see below). Using a stacked bar chart made it much more difficult to read the value of the different error bars, as well as making it almost impossible to see the contribution of excess change, due to it being overshadowed by the larger terms.

Instead, we have made changes to improve the readability of the original figure: we have removed the error bars and instead used shading to represent the standard deviation. We have also increased the size of the individual markers, so they are easier to see despite overlapping at some points. We have also changed the lines to a dotted line, to ensure the emphasis is on the individual data points and so is not suggesting a linear trend.



Line 255. We have noticed that the ship transects occurred at different seasons (see table A1). Do the authors think that the different temperatures, primary production, etc., of the different seasons could impact the results? In the abstract, the authors mentioned ‘This remineralization-driven change may be caused by a change in the supply of biological material to depth...’, We assume the large organic particles would have a different export rate in different seasons since it’s a function of primary productivity and mixed layer depth. We would expect the authors to discuss a bit more about how they treat such variability.

While we expect the largest seasonal changes to occur in the upper 150 m of the water column, which we have excluded from our analysis, we believe any deeper seasonality is not large enough to alter our conclusions. The 1992 cruise was the only cruise to take place during summer, but since it is taken as a baseline to compute changes from year to year, while the different time of year may influence the quantitative differences between the years, it will not affect the year-to-year trends since they are all calculated from the same baseline. The 2004 cruise also occurred at a slightly different time of year, from April-May, that cruise sees the same trends as other years, with deoxygenation during 2004 due to excess and remineralisation changes being larger than in 1998, but smaller than those in 2010. We have now discussed seasonality within the discussion of the manuscript:

“The six cruises on the A05 transect generally took place between December and March, however two cruises did not occur during this time frame (1992 and 2004, see Table A1), meaning the results could be impacted by seasonal changes. To account for this, we excluded the upper 150 m from our analysis - the depths where we expect the greatest seasonality to occur and where they are clear in the initial temperature, DIC and oxygen profiles (Fig. 1b-d). The 1992 cruise occurred during summer, but since it was used as a baseline to calculate the changes between years, while this may lead to biases in the quantitative results, it should not affect the observed long-term trends. In the mechanisms that we see the clearest trends, i.e. in excess and remineralisation changes, the same trends were observed in 2004, suggesting that any seasonal changes deeper than 150 m are not large enough to impact the trends we see in the results.” (Lines 320-327)

Line 270. The export ratio determines what fraction of productivity is exported, so a change in productivity does not necessarily have to lead to an equal change in export amount. It would be good to acknowledge this here and the consequences for the authors' conclusions.

Thank you for the suggestion. The following has been included in the discussion: "... there has been little change in primary production in the surface of the subtropical North Atlantic over the same time period (Macovei et al., 2019). This suggests that either there is has been change in the export ratio, with less of the productivity exported to depth, or that changes in large-scale circulation are driving the increased remineralisation." (Lines 293-295)

Line 285. 'The excess oxygen change has already doubled in magnitude between 1992 and 2015.' Can you report the value of this magnitude?

This has now been changed to:

"The excess oxygen change has already more than doubled in magnitude between 1998 and 2015, from $-0.16 \mu\text{mol kg}^{-1}$ to $-0.47 \mu\text{mol kg}^{-1}$ in the upper 150-500 m." (Lines 315-316)

Line 305. The conclusion part is too simple to summarize the key results of this study, including the methods used and the trend (magnitude, proportion, caveats, etc.) found from these GOSHIP transects. This is an important section; thus suggest the authors add more detail to this part.

The conclusions have now been extended to include further information about the method, and the observational data the method was used on. We also further discuss the magnitude of the remineralisation change and that we can only speculate and what is driving that change in remineralisation without further work.

Line 310: Where is Appendix A?

Appendix A contains only the table of information about the individual cruises. A section title has now been added to make this clearer.