

Author reply Referee 2 comment “Millennial changes in North Atlantic oxygen concentrations”

Babette Hoogakker and colleagues present new Dd13C measurements – a proxy allowing quantitative changes in dissolved O₂ concentration to be reconstructed - from intermediate-depth sediment core ODP 1055. The time interval of interest encompasses the last glacial inception as well as several transient cooling events associated with ice rafting and meltwater release to the North Atlantic. The authors compare their newly generated reconstructions with previously published observations from the Iberian Margin.

They show – somewhat unexpectedly – that changes in oxygenation in intermediate and deep water masses followed a similar pattern during the interval 60-80 kyrs. This is seemingly at odds with the notion that NADW formation was reduced during stadials - allowing nutrient-rich, oxygen depleted waters of southern origin to propagate northward - while intermediate water masses were better ventilated. The authors reconcile this apparent discrepancy by invoking (local?) changes in respiration rates, possibly overprinting the ventilation signal.

Moreover, Hoogakker and colleagues show that their data are in good agreement with climate model outputs, which predict a general decrease in oxygenation in the North Atlantic during cold intervals.

I find the paper interesting in that it highlights the potential of the proxy used to quantitatively reconstruct past changes in oxygenation. Hoogakker has done a great job in refining the proxy, which will undoubtedly prove to be very helpful to deepen our understanding of past changes in the carbon cycle. This being said, I find the paper largely reworks arguments that were developed in a previous manuscript (Hoogakker et al., 2015, Nature Geoscience), thereby somewhat limiting its impact. Nonetheless, given the potential application of the proxy and its usefulness for the scientific debate, I would support publication of the present study, provided the rather minor comments outlined below can be addressed.

General comments -

I would urge the authors to better describe the parameters influencing local oxygenation in their introduction. In particular, the authors need to better explain the often interwoven influence of physical vs. biological mechanisms on oxygen levels. (A useful approach, I find, is provided by Schmittner et al., 2007, Paleoclimatology or Jaccard et al., 2014, Oceanography).

We propose to add the following lines to the introduction ' Oxygen is vital to all aerobic life. Oxygen solubility in seawater is highly temperature dependent, with salinity playing a secondary role. The [O₂] of a (deep or intermediate) water mass at a particular location is determined by its initial concentration at the convection area, the amount of respiration it has undergone, and mixing with other water masses. Both oxygen supply and consumption are ultimately driven by ocean circulation and biology (Schmittner et al., 2007). Climate models predict that oxygen concentrations in the ocean will decrease substantially in response to anthropogenic climate change.'

I also find the discussion related to the ODP 1055 record (p. 12959, l. 5-27) clumsy and confusing (see below).

Detailed comments -

p. 12947 l. 4 - affiliation – University of Oxford **This will be corrected.**

p. 12948 l. 11 – . . . at intermediatedepth core. . . **This will be corrected.**

l. 20 – export production instead of productivity **This will be corrected.**

l. 24 – . . . can be linked to increased export of organic material from the surface ocean and its subsequent remineralisation in the water column and the sediment. **This will be corrected.**

p. 12949 l. 1 – 231Pa/230Th **Please could the reviewer be more specific here, we do not understand the comment..**

l. 16 – overturning **This will be corrected.**

p. 12952 l. 8 - . . . oxygen and carbon are stoichiometrically linked. . . **This will be corrected.**

p.12953 l. 1 – please either remove etc or be more specific. **This will be corrected.**

l. 2- please delete quantitative **This will be corrected.**

p. 12954 l. 4-7. This sentence seems out of place here. It is meant to explain that the changes in seawater [O₂] do not have large scale repercussions for marine life (e.g. [O₂] values never become hypoxic/anoxic), but they are large.

p. 12955 l. 16 – remove etc l. This will be corrected.

18-23. Can you provide some hypothesis, as to why there is so much discrepancy in the downcore δ¹³C signal derived from intermediate-depth sediments?

Actually, after revisiting there does not seem to be a consistent trend of heavier benthic δ¹³C in the northeast Atlantic. Dickson et al. (2008) had their axis reversed and closer inspection reveals a more complicated picture, with heavier δ¹³C during H5a and lighter δ¹³C during H4. In addition the depiction in

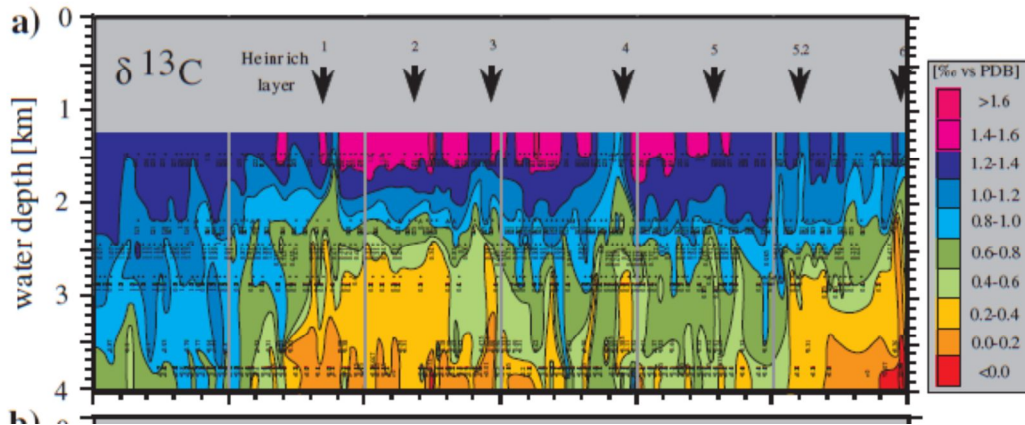


Figure 8 of Sarnthein et al. (2000), shown above, also does not show a consistent picture, with overall more depleted values during H5 and 4, depleted deep, but uncertain intermediate, no signal for H2, whereas possible H1 shows heavier values. We propose to rephrase this line to 'High resolution, well dated, intermediate depth North Atlantic records most from the northeast Atlantic also generally show lower benthic δ¹³C during Heinrich events (Sarnthein et al., 2000; Chapman and Shackleton, 2002; Rasmussen et al., 2003; Peck et al., 2006; Dickson et al., 2008; Thornalley et al., 2010) whereas ODP 1055 from the northwest Atlantic, featured here, mostly shows hardly any change (Thornalley et al., 2013).'

p. 12957 l. 9 – is the O₂ concentration difference inferred for the LGM (i.e. 200 ± 17 umol*kg⁻¹) and MIS6 (i.e. 180 ± 17 umol*kg⁻¹) statistically significant?

We believe it is informative to show the range for the two glacials with the error.

l. 12 – please add adequate references.

l. 15. Böhm et al., 15, Nature seems a more adequate reference here.

We can add this reference.

l. 13. McManus et al., 2004 l. 15. Heinrich Stadial 1 This will be corrected.

p. 12957 l. 15 – this observation is also valid for shallower records (Praetorius et al., 2008, Nature Geoscience)

We can add a sentence (p 12958 l 19) 'In the NE Atlantic Praetorius et al. (2008) find, using bottom flow speed reconstructions, a decrease in flow vigour of intermediate water flow in the NE Atlantic during Heinrich Stadial 1.' Plus line 28 'These observations suggest that a stronger intermediate depth AMOC cell did not influence the NE Atlantic.'

p. 12959

l. 1 – please add reference This line provides a summary statement of the foregoing two paragraphs.

l. 25 – please add reference Hoogakker et al. (2007) observed diatom mat deposits in sediments from ODP 1060. We can add a reference to Lippold et al. (2009) which nicely illustrates this for Bermuda Rise Site ODP 1063.

l. 26-28. This argumentation is confusing and needs to be rephrased. While I agree that there could have been more organic carbon exported during Heinrich stadials in the Atlantic, I do not agree that this implies a strengthening of the biological pump.

Evidence suggests that the global efficiency of the biological pump was reduced during HS1, allowing carbon to be released from the ocean interior (e.g. Galbraith Jaccard, 2015, QSR).

I guess the argument here, was that enhanced local export production lead to enhanced oxygen removal during Heinrich stadials at intermediate depths. One should keep in mind

that under colder temperatures, the remineralization length scale increases (e.g. Matsumoto, 2007, GRL), which would have shifted the OM remineralization maximum to the core of NADW (Kwon et al., 2009, Nature Geoscience), consistent with enhanced O₂ depletion in the deep Atlantic, but somewhat at odds with the observations presented for core ODP 1055.

This is an interesting suggestion, although it seems it really depends which study one looks at. We can delete 'strengthening of the biological pump'.

p. 12960 l. 1 – Again, I don't think there is any evidence supporting a strengthening of the biological pump during North Atlantic stadials. A reduction of the relative contribution of northern sourced waters in ventilating the global deep ocean during North Atlantic stadials would contribute to weaken the biological pump globally (e.g. Sigman et al., 2010, Nature). Increased export does not necessarily imply a strengthening of the biological pump.

Again, we can delete 'strengthening of the biological pump'.

l. 9-12 l. 24-25. I agree that the data compares well with the UVic model outputs – and this is great. However, the UVic model also predicts decreased export production in the North Atlantic during periods of weak NADW (see Schmittner, 2005, Nature, Fig. 1 g/h) resulting from a shoaling of the winter mixed layers, which is at odds with the argument put forth by the authors (p. 12959). One cannot pick the argument that fits the main hypothesis and not mention the model outputs that don't fit the observations.

The UVic model indeed predicts decreased export production over areas of the North Atlantic during periods of weak NADW. Presumably the shoaling of the winter mixed layer discussed by Schmittner (2005) relates to the area in the North Atlantic where freshening takes place (and where a decrease in export flux is observed), but not the subtropical gyre. We will include a reference to an additional study by Menviel et al. (2015), who, using LOVECLim and UVic, also show a global export decrease in export production during freshwater addition experiments. It is important to note that the models do show increased export production in large areas of the Atlantic Ocean, particularly UVic.

Interestingly also the study of Menviel et al. (2015) suggest an increase in the efficiency of the biological pump in response to an increase in nutrient utilization efficiency.

In our revised manuscript we propose to change lines 5 to 8 to 'In terms of biological mechanism driving North Atlantic seawater [O₂] changes during Heinrich events the picture is not clear. Model simulations suggest that export production during Heinrich events was globally reduced (Schmittner et al., 2005; Mariotti et al., 2012, Menviel et al., 2015). Interestingly, while Mariotti et al. (2012) suggest an overall decrease in export production in the North Atlantic, model simulations by Menviel et al. (2015) show increases across large areas in the Atlantic.'

Fig. 5 – error bars are not visible for all the measurements. Does this imply that the error bars are smaller than the symbol size?

Error bars are only plotted for $\delta d^{13}C$ of 2.35 and less, above this value the calibration does not work, and no [O₂] values are given. We will revise the figure as the for certain intervals only one direction of the error bar is shown.