Interactive comment on:

"Modulation of the North Atlantic Deoxygenation by The Slowdown of the Nutrient Stream"

by F. Tagklis, T. Ito, A. Bracco

*In black are the original comments by the reviewers, which is followed by our responses in blue.

Anonymous Referee #1: (Major Revision #2)

Line 84: Please provide a citation for Climate Data Operators.

Figure 5: I do not see the black dots indicating significantly regions as described in the caption.

Line 181: Suggested edit: 'temperature change by 1ºC' to 'temperature increase by 1ºC'. A change can be in either direction, but the statement concludes with an O2 solubility decrease, implying a temperature increase.

We have changed and clarified the suggested points in lines 84, Figure 5 and line181 accordingly. The size of the dots representing statistically significant changes was also changed for figures 4, 5, 6.

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Anonymous Referee #2: (Major Revision #2)

The study examines the centennial changes in upper ocean phosphate and export production from a suite of 7 CMIP5 models. There is a centennial decline in the upper ocean phosphate in all the models apart from the IPSL ones for the North Atlantic. This change is qualitatively associated with a weakening in the meridional ocean overturning and its nutrient stream. This connection is plausible, but is not fully confirmed in this study.

The authors have strengthened the manuscript by including 3 additional models and an analysis of the northward transport of nitrate at 10N over the upper 700m for all the models (in Fig. 10). The inclusion of the nitrate transport shows a decline in the normalised northward component associated with the meridional overturning in all the models apart from the IPSL-CM5A-LR one for the North Atlantic. This signal again lends support to the authors' hypothesis that the decline in the nutrient stream leads to the decline in nutrients in the North Atlantic basin.

However, as raised by the reviewers and the Editor, there are a range of other processes that might also be associated with the nutrient decline. I suspect that the authors are right in terms of their interpretation, but a higher level of evidence needs to be reached to support this plausible assertion.

In my view, a further simple calculation is required where the convergence of the Atlantic nitrate transport between 10N and a northern latitude circle is compared with the tendency in the mass-weighted nutrients within that enclosed volume, such that both terms have the same units (like mol/s). While there need not be an exact match due to other contributions, to be fully convincing, this comparison should at least have both the terms having a comparable magnitude and sign.

The authors may think that they have already shown that comparison, but the side panels in Fig. 10 only show the normalised time series of the nitrate transport and the nitrate inventory, which is not as convincing as the actual contributions to the budget, where terms have the same units and a convergence in nitrate transport should equate to a positive tendency.

Including this budget comparison (without the normalisation) would remove doubts as whether the agreement in the sign in the decline in the nutrient stream and the nutrient stock is significant. The work would be more convincing if applied to all the models and I would have thought would be relatively straight forward given the rest of the work that has been completed; however, alternatively, I would be happy to see a more detailed nutrient budget performed for one of the representative models.

I recommend that the authors take on board this recommendation so that they are then able to provide a more convincing and substantial contribution, which is identifying an important climate change mechanism affecting biological productivity.

We appreciate the reviewer’s comments. We have tried to address and clarify the suggested points as follows.

Following the reviewer’s suggestion, we include an estimate of the regional nutrient budget using GFDL-ESM2M as a representative model. Following the geographical boundaries of the previous analysis, we consider a control volume enclosing the STNA with the boundaries at approximately 10^{o}N-48^{o}N, 80^{o}W-10^{o}W and 700 meters depth using the native model grid. We calculate and present all lateral nutrient transport terms in and out of the control volume, all in units of moles per second. Zonal and meridional fluxes are defined positive eastward and northward, and the vertical flux is defined positive upward.

Figure 11a shows the changes in magnitude and the sign of each component during the historical period 1861-2005 and rcp8.5 period 2006-2100. The northward supply of nutrients at 10^{o}N ($vPO4_{(10oN)}$) has the most significant decline among the lateral transport terms and a comparable magnitude with the northward transport of nutrient at 48^{o}N ($vPO4_{(48oN)}$). The western boundary transport component at 80^{o}W ($uPO4_{(80^{o}W)}$) represents the net nutrient supply through the Florida current which loses half of its magnitude by the end of the 21st century. The eastern boundary component at 10^{o}W ($uPO4_{(10^{o}W)}$) remains mostly unchanged. The vertical component at 700 meters depth ($wPO4_{(700m)}$) is negative (downwelling) with decreasing magnitudes. The signs and the magnitude of the changes in the lateral and vertical transport terms are consistent with the weakened advective nutrient transport, providing additional support to our hypotheses.

The flux convergence of the (resolved) advective transport must be balanced by the time derivative of the nutrient inventory and the net biological nutrient sources/sinks. Sub-grid scale parameterizations could also contribute to the regional nutrient budget. It is difficult to precisely close the nutrient budget with the available dataset. However, we can still integrate over time the flux convergence of the advective transport to calculate the 'estimated' nutrient inventory ($PO4_{estimated}$). Net advective convergence is positive, and its integral gradually increases over time because it does not include the nutrient uptake and export by biological processes (Bio). To account for the baseline pre-industrial biological component (Bio), we first determine the residual between the $PO4_{estimated}$ and the PO4 as Residual (=$PO4_{estimated}$ - PO4). Then the pre-industrial estimate of Bio is estimated as a linear trend based on the first 60 years (1861-1920) of the Residual. Then the corrected $PO4_{estimated}$ is determined as the temporal integral of the advective flux convergence minus Bio. Then the $PO4_{estimated}$ time series reflects the change in STNA nutrient budget if there were no changes in biological sources/sinks (constant Bio). Figure 11b shows that the decline of $PO4_{estimated}$ is much larger than that of PO4. After the year 2005 and during the rcp8.5 period the actual PO4 inventory does not decrease as much as the estimated inventory $PO4_{estimated}$ due to the weakened biological export of nutrients. This result is consistent with the weakened biological productivity of the North Atlantic as well as the circulation change as the main driver of the nutrient decline in the basin.

$$\frac{\boldsymbol{d(PO4)}}{\boldsymbol{dt}} = \boldsymbol{vPO4_{(10^oN)}} - vPO4_{(48^oN)} + \boldsymbol{uPO4_{(80^oW)}} - uPO4_{(10^oW)} + \boldsymbol{wPO4_{(700\,m)}} - \boldsymbol{Bio} \quad (\boldsymbol{eq.1})$$

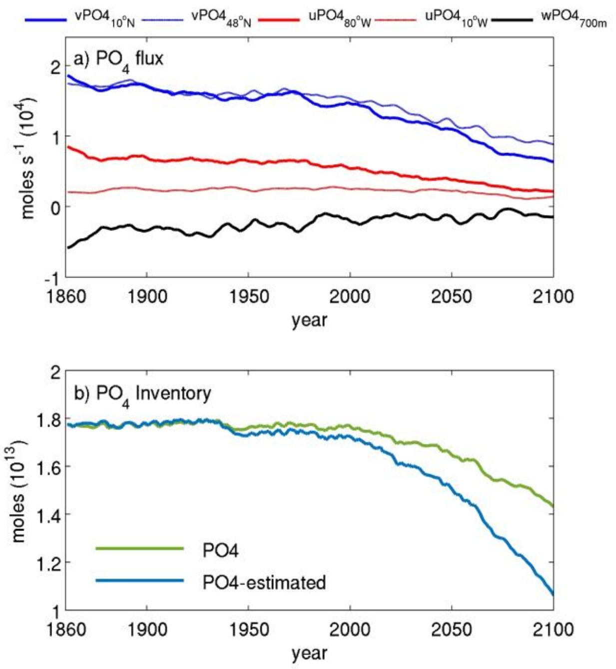

Figure 11 a) Lateral nutrient fluxes in and out of a box enclosing the subtropical North Atlantic area with boundaries 10ºN-48ºN, 80ºW-10ºW and 700 meters depth. All in units of moles/sec. b) Nutrient inventory integrating lateral fluxes over time (light blue) and compared with the actual nutrient inventory (light green).