

Reply to the Review of the Referee #2 (Anonymous)

(**RC**: Referee Comment; **AR**: Author's Responds)

First of all, thank you very much for reviewing our manuscript thoroughly and for the helpful comments and suggestions. We try to include as many comments and suggestions as possible which help us to improve our manuscript.

Abstract

Page 1, line 20

RC: I would remove 'strong' here, as N^* of $-1 \mu M$ would not generally be considered "a strong N deficit".

AR: We agree with you and have omitted "strong" here.

Page 1, lines 21-23

RC: Please clarify what you are referring to here using "preformed versus regenerated". The preceding sentence referred to nitrate isotope signals coming from SAMW and from denitrification in the Arabian Sea. Where is the 'regenerated' signal that you are referring to?

AR: The nitrate that is added by N_2 -fixation and immediately consumed (assimilated) in the surface layer is meant as regenerated nitrate, as well as the remineralised nitrate by nitrification. These are in situ processes contrary to the preformed isotopic composition of nitrate induced by the lateral influence from the neighbouring water masses. We will rewrite the sentence to make this clearer.

Page 1, lines 23-25

RC: If there is significant N_2 fixation, I would not expect low nitrate to phosphate ratios. Revisit the N_2 fixation discussion below.

AR: Enhanced N/P ratios in N-fixing organisms has been reported and would introduce these enhanced N/P ratios also to the water mass as the N-fixers are mineralised. This process is reflected in enhanced N/P ratios. The way we calculated the contribution from N_2 -fixation is thus a minimum estimate of N contribution from N_2 -fixation. If part of the P was also from N-fixers and if the N/P ratio of N fixers was known, their contribution could have been better estimated. However, we cannot be sure about the N-fixers N/P ratio. We will, however, examine this carefully in the revised version and improve this part including the dual isotope approach.

Introduction

Page 2, line 21

RC: I think a reference to Gruber and Sarmiento, 1997 would be appropriate here.

AR: We will add the reference of Gruber and Sarmiento (1997).

Page 2, lines 29-30

RC: The isotopic fractionation factor, ϵ , relates the instantaneous product, not the accumulated product, to the substrate. Though neither is explicitly stated, I think the implication is that this always holds true. This should be clarified.

AR: We will examine this carefully and clarify this in our revised version.

Materials and Methods

Page 6, line 14

RC: How is the 'single point correction' for $\delta^{15}\text{N}$ applied? Is this simply a standard subtraction?

AR: We will correct the method section, because we indeed do not use a single point correction but rather a two-point correction referred to IAEA-N3 ($\delta^{15}\text{N-NO}_3^- = +4.7\text{‰}$ and $\delta^{18}\text{O-NO}_3^- = +25.6\text{‰}$) and USGS-34 ($\delta^{15}\text{N-NO}_3^- = -1.8\text{‰}$ and $\delta^{18}\text{O-NO}_3^- = -27.9\text{‰}$) for $\delta^{15}\text{N-NO}_3^-$ and $\delta^{18}\text{O-NO}_3^-$.

Results

Page 6, line 29

RC: What water mass does the 34.6 PSU feature represent?

AR: AAIW (Antarctic Intermediate Water) is characterised by a salinity minimum of <34.6 PSU at a core density of 27.2 kg/m³. There is a mistake on page 10, line 2: "The salinity minimum (<34.9 PSU) south of 15° S ...". We will correct this to "The salinity minimum (<34.6 PSU) south of 15° S...". Sorry for this misunderstanding.

Figure 2

RC: It might be more helpful to include contours for the potential density surfaces, rather than contouring the same properties represented on the color bar.

AR: This is a good remark and is a chance to include more information into the sections. We will change the contour lines for the potential density surfaces.

Pages 7 and 8

RC:

(1) I don't understand the choices behind what is shown in Tables 2 and 3. Why are these specific density/depth intervals selected, and why look at different density levels in the different latitude zones? Why are only one nitrate and

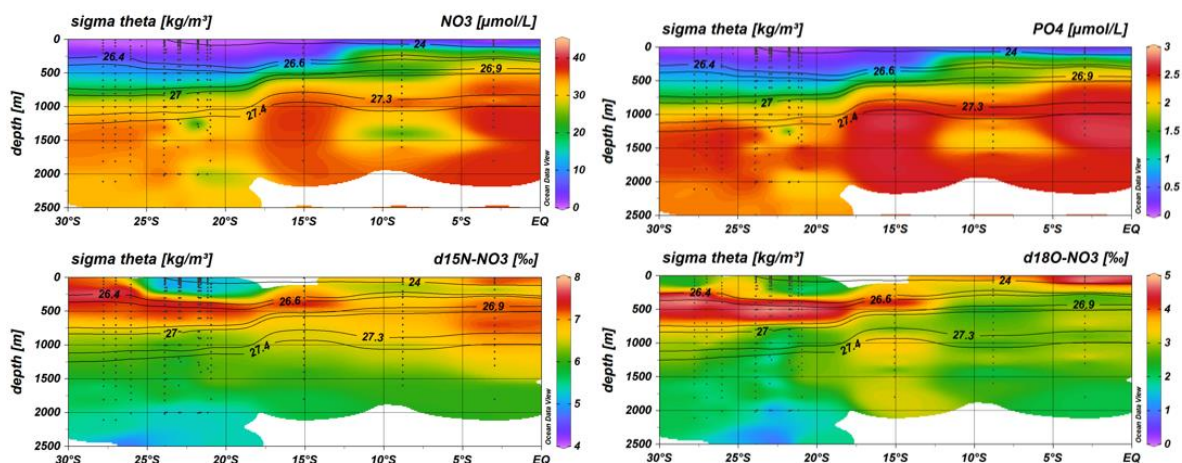
phosphate concentration (Table 2) or nitrate $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ value (Table 3) given for each line? How many measurements are included in these values? Shouldn't there be a range or uncertainty given for these if they derive from a range in latitude?

(2) Throughout this presentation of results in sections 3.2 and 3.3, I found referring to Figure 5 more useful than consulting Tables 2 and 3. I would suggest moving Figure 5 earlier in the paper, and removing Tables 2 and 3, or perhaps moving them to the supplement, unless their relevance can be better explained.

AR:

(1) For Table 2 and 3 we chose these depth intervals to provide average nitrate/phosphate concentrations (Table 2) and $\delta^{15}\text{N}/\delta^{18}\text{O}$ values (Table 3) for each water mass (along sigma-theta surfaces) in their specific latitudinal extent and thickness. Because the water mass distribution changes along the latitudinal transect, we chose 3 or 4 different latitudinal clusters to represent the change of nitrate/phosphate concentrations in Table 2 and isotopic compositions in Table 3. In Table 3 we decided to add a fourth latitudinal cluster to represent the divergent higher $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ values between 27.78°S and 26.05°S . For a better understanding of these Tables, it might be better to show the sigma-theta intervals rather than the depth intervals and to add the associated water masses to the density surfaces in the specific latitudinal section. We showed only one value for each latitude and depth range because these are averages of one to ten single values. You are right that we have to add a range for the average values. The uncertainties of each single measurement are shown in the supplement Table S1 and S2.

(2) If we move Figure 5 into the results we have to remove the overlay of water mass boundaries in the panels, because they were added as a consequence of the water mass discussion section. We thought intensely discussed this issue with all co-authors where the best position of the water mass section would be within our manuscript. In the end, we decided to present this section with the distinct classification of the different water masses and the resultant water mass distribution model in a separate discussion section because of the high portion of discussion rather than just the presentation of results. In our water mass analyses, we use many different sources, describing water masses in the world's ocean and when available from expedition in the Indian Ocean, but they are quite rare and no water mass model existed for our study area. Therefore, we decided to present the water mass distributions in an own discussion section and not as a part of the results. Consequently, we think that, Figure 5 with the overlying water mass distribution belongs to the discussion section. However, it would be a good opportunity to leave Figure 5 (a-f) in section 4.2.1, but add only nitrate, phosphate and nitrate isotope color sections without overlying water mass distributions (see example below; like Figure 2a and b for salinity and oxygen) to the results (3.2) and move the reworked Tables 2 and 3 to the supplementary materials.



Example for nitrate, phosphate and N and O isotope transects

Page 7, line 6

RC: I would delete ‘strongly’. When working in oligotrophic areas, I’m not sure 5.9 μM nitrate qualifies as “strongly depleted”. Otherwise, you could perhaps cite the concentration of nitrate in the surface waters, rather than at 310 m.

AR: This is a good objection. We will rewrite the sentence.

Discussion

Page 10, line 27

RC: Please clarify “decrease of the oxygen minimum”. Do you mean that the oxygen concentration is increasing? If so, please rephrase.

AR: Yes, “decrease of the oxygen minimum”, means that the oxygen concentration increases, we will rephrase the sentence.

Figure 3

RC: I didn’t find this Figure necessary, and suggest that it be moved to the supplement.

AR: This Figure is intended to show how we defined the different water mass boundaries and how the water mass distribution model was generated. We think the presentation of these diagrams is very important for our water mass analyses and we would like to leave this Figure in the main text, unless you would necessarily move the Figure to the supplement.

Figure 4

RC: I think this Figure is extremely helpful for thinking about the water mass structure of the region! My only question is what determines where the lines dividing water masses are drawn? Are these specific sigma theta surfaces? Please clarify.

AR: To generate this water mass distribution model we use sigma-theta surfaces, and salinity and oxygen distribution (see Figure 3) to define the different water masses in the latitudinal transect. We separate the transect in

three latitudinal sections (see Figure 3): 20.36-27.78°S, 15.08°S and 2.98-8.81°S to represent the change of the water mass distribution along our transect. Therefore, we thought the presentation of Figure 3 helps to understand the generation of Figure 4.

Figure 6

RC: The Figure legend states that the color bar indicates potential density, but what is actually used is depth. Perhaps sigma theta would, in fact, be better.

AR: Sorry for this mistake! First, the color bar represents sigma-theta and was changed later into a depth color bar without a correction of the Figure legend. We will correct this and change the color bar for sigma-theta.

Page 15, line 16

RC: Doesn't iron availability also play a role in incomplete nitrate assimilation in the Southern Ocean?

AR: We will consider this and rewrite this paragraph.

Page 17, line 3

RC: Please clarify "lower water depths". Do you mean shallower or deeper?

AR: Sorry for the misunderstanding, we meant shallower water depths. We will make this clearer.

Figure 8

RC: The yellow star representing the mean nitrate $\delta^{15}\text{N}$ does not stand out. I would suggest making this symbol a different color or shape. Also, please provide the slope of the solid line in the Figure legend.

AR: We will highlight more clearly the symbol for the mean nitrate $\delta^{15}\text{N}$ and add the slope of the solid line in the Figure legend.

Page 17, line 11

RC: Typo, should be 'SAMW' rather than "SAWM".

AR: We will correct this mistake.

Page 17, line 14

RC: Please give Sigman et al., 2005 reference to $\Delta(15,18)$. Rafter et al (2013) is also a good reference, but uses $\Delta(15-18)$ instead.

AR: In our revised version we will reconsider the use of $\Delta(15,18)$ because of the diverse source waters in our study area. Better would be the tracer $\Delta(15-18)$ from Rafter et al. (2013), who used only the difference between N and O isotope signatures which is more useful in regions characterised by a variety of water masses. We will consider this in the revised version.

Page 18, line 16

RC: I would include a reference here to Gruber and Sarmiento 1997 for their seminal work in this area.

AR: We will include the reference to Gruber and Sarmiento (1997) here.

Page 18, line 24

RC: One could also reference work in the Atlantic from Knapp et al., 2008, and a variety of work from the Pacific.

AR: We will consider this and add more information from studies in the Atlantic and Pacific (Knapp et al., 2008 and Bourbonnais et al. 2009, etc.)

Page 19, lines 7-8

RC: What are the implications of assuming Redfield stoichiometry here?

AC: We will examine and clarify this in the revised version.

Page 19, line 10

RC: This equation appears incomplete, if not incorrect. From the text, I would not expect PO₄³⁻-sample to appear in the denominator.

AR: Sorry for this mistake, you are right, the equation will be $\text{NO}_3^- \text{-cal} = \text{NO}_3^- / \text{PO}_4^{3-} \text{-cal} * \text{PO}_4^{3-} \text{-sample}$

Page 19, line 12

RC: What is the N:P ratio assumed for newly fixed N? This seems important to the calculations performed here.

AR: We assumed an elevated N/P ratio for newly fixed N compared to the preformed N/P ratio in our study area (13.25 in the IOSG and 14.25 in the south equatorial Indian Ocean). We observe these higher N/P ratios in our surface samples (low nitrate concentration of <5 μM) in Figure 9a.

Page 19, lines 20-23

RC: A newly fixed δ¹⁵N of 4.8‰ is not within the range of expected values for N₂ fixation. This seems problematic, and requires reevaluation and justification of the approach used to arrive at this value. In my mind, a value of +4.8‰ argues against this N deriving from N₂ fixation. What other explanations have the authors considered?

AR: Indeed, we found evidences for N₂-fixation: 1) Elevated N* values of >2 μM in surface waters south of ~15°S. (2) Even though a δ¹⁵N of 4.5 to 5.0 ‰ is not a clear evidence for the input of low δ¹⁵N by N₂-fixation, the distinct decrease from subsurface values within the SAMW with values of >7 ‰ and highest values of ~8 ‰ indicate an upward decrease of 2-3.5 ‰. This decrease can only be explained by the input of fixed N into the surface layer. Additionally, studies in the Atlantic indicate the similar difference of 3 ‰ (from 5 ‰ to 2 ‰), i.e Bourbonnais et al. (2009). Furthermore the surface δ¹⁵N values are lower than

the $\delta^{15}\text{N}$ deep water mean of >5.5 ‰. (3) The calculated value of $+4.8$ ‰ is just a simple calculation there we take the calculated 30% of new N-input by N_2 -fixation and compare this value with our observations assuming the SAMW as N source with a $\delta^{15}\text{N}$ of >7 ‰. When the source would have higher $\delta^{15}\text{N}$ values, than we would get higher $\delta^{15}\text{N}$ values for the newly fixed $\delta^{15}\text{N}$ in surface waters. In the revised version, we will make our arguments for N_2 -fixation clearer.

Figure 9

RC: It is difficult to distinguish the symbols used to represent the two geographic areas in panel a. What calculation is used to derive the grey line in panel a?

AR: We will choose different symbols for a better differentiation in Figure 9a. The grey solid line indicates the calculated N-assimilation (regression line of $\text{NO}_3\text{-cal}$ vs. $\text{NO}_3\text{-cal}/\text{PO}_4^{3\text{-cal}}$) with a preformed $\text{NO}_3\text{-cal}/\text{PO}_4^{3\text{-in}}$ ratio of 13.25 for the region of the IOSG and 14.25 for the southern equatorial Indian Ocean and progressive nutrient assimilation with a Redfield ratio of 16 ($\text{NO}_3\text{-cal}/\text{PO}_4^{3\text{-ass}}$).

Page 20, line 16

RC: Is low temperature the only other possible explanation? Increasing numbers of reports are finding N_2 fixation at low temperature, thus the temperature limits seem to be a less convincing argument. What other contributing factors could be here?

AR: The sudden change in $\delta^{15}\text{N}$ and N^* is difficult to explain in the gyre as nutrients are not increasing. We have no data on micronutrients but find it unlikely that these change significantly within the gyre. Therefore, the only feasible explanation seems to be the temperature drop. However, we will stress the contradictory literature in the revised version.

Page 21, lines 10-11

RC: Can you make any connection here to the results of Martin and Casciotti, 2017 from the Arabian Sea?

AR: We will consider to add some sentences with respect to Martin and Casciotti (2017), but their work focuses on the Arabian Sea and not on the influence from the Arabian Sea on the south Indian Ocean.