

## Response to Reviewer 1

Thank you for your review.

Balancing the number of acronyms used in a manuscript is always challenging. In response to this comment, we have reduced the number of acronyms in the conclusions section. We find that using the acronyms for each process (e.g. NAR and NIR) in the rest of the text is less confusing than spelling out  $\text{NO}_3^-$  reduction and  $\text{NO}_2^-$  reduction, since it is easier to mistake the 3 and 2 in the subscripts than the “A” and “I” in the acronyms. There is no perfect solution to this, and we hope that removing the process acronyms in the conclusions will be helpful in this regard. In addition, we have opted to retain widely used three-letter acronyms for chemical species (DIN, DON, PON, etc.), but have revised the less common two-letter acronym ‘ON’ to ‘organic N’ throughout. We believe this strikes a balance between both clarity and brevity.

A brief comment on the importance of improving N cycle models by adding  $\text{NO}_2^-$  as a tracer has been added to the abstract.

### Specific comments

- Page 2, line 16: Rephrased as requested.
- Page 2, line 17: Rephrased as requested.
- Page 3, line 24: Rephrased as requested.
- Page 3, line 31: The optimization itself was not conducted using the sensitivity analysis, but the optimization procedure is discussed in Section 2.6. Sensitivity analysis was performed in order to narrow the set of parameters that was optimized, since there are too many parameters in the model to optimize them all concurrently due to computational limits.
- Page 4, line 4: Rephrased as requested.
- Page 4, line 30: Additional comments added to reference  $\text{NH}_4^+$  accumulation in ODZs.
  - Added text: “Though  $\text{NH}_4^+$  has been observed to accumulate to micromolar concentrations in ODZs (Bristow et al., 2016; Hu et al., 2016), this occurs largely in shallow, coastal shelf regions, which are not resolved by the model.”
- Page 6, line 15: References added for  $r_{\text{air}}$  (Mariotti, 1983).
- Page 7, line 16: The references to the pe ratio have been changed to  $P_e$  in both equations and the text to improve clarity.
- Page 7, line 22: Sentence has been restructured to avoid starting with a symbol
- Section 2.3.2: A brief discussion of the exclusion of riverine N inputs from the model has been added to the beginning of the section.
  - Added text: “In our model, atmospheric deposition and  $\text{N}_2$  fixation are the only sources of bioavailable N in the model. These are the two largest sources of N to the ocean (Gruber and Galloway, 2008). We do not consider the third largest source of N, riverine fluxes, in the model due to lack of coastal resolution and the expectation that much of the river-derived N is denitrified in the shelf sediments (Nixon et al., 1996; Seitzinger and Giblin, 1996). This would potentially impact

the surface  $\text{NO}_3^-$  and  $\delta^{15}\text{N}_{\text{NO}_3}$  but the overall contribution to the N budget would be negligible, especially considering the coarse resolution of the model.”

- Page 8, line 4:  $\text{DON}$  and  $\text{NO}_3^-/\text{NO}_2^-$  must be considered separately in order to introduce dependence on two N species for  $\text{NO}_3^-$  reduction and  $\text{NO}_2^-$  reduction, since these heterotrophic processes require both organic N and either  $\text{NO}_3^-$  or  $\text{NO}_2^-$ . In order to use the simple linear model setup,  $\text{DON}$  and  $\text{NO}_3^-/\text{NO}_2^-$  cannot be variables/unknown at the same time. Additional explanation can be found in Section 2.3.1, and some additional discussion has been added to the line in question.
  - Added text: “The assimilation rates for  $\text{DON}$  and  $\text{PON}$  must be calculated using observed surface  $[\text{NO}_3^-]$ , rather than modeled  $[\text{NO}_3^-]$ , in order for the heterotrophic processes of  $\text{NAR}$  and  $\text{NIR}$  to be dependent on both organic N and  $\text{NO}_3^-$  or  $\text{NO}_2^-$  availability, respectively.”
- Page 9, line 1: This sentence has been clarified to indicate that having a variable  $^{14}\text{k}_{\text{sol}}$  that accurately represents slower ON remineralization under low  $\text{O}_2$  conditions would be a refinement that could be incorporated in future model versions.
  - Added text: “A spatially variable  $^{14}\text{k}_{\text{sol}}$  that accounts for lower apparent values in  $\text{ODZs}$  is a refinement that could be introduced in future model versions.”
- Page 11, line 1-3: taylor to do.
- Page 12, line 3: Cutoff points discussion has been rephrased to clarify that they are the transition points between the piecewise segments of the  $([\text{O}_2] - [\text{NO}_3^-])$  vs. sedimentary denitrification rate relationship.
  - Added text: “In order for sedimentary denitrification to be properly implemented in our linear model, we broke the original non-linear relationship into three roughly linear segments to create a piecewise relationship between  $([\text{O}_2] - [\text{NO}_3^-])$  and sedimentary denitrification rate. We obtained three linear relationships between  $([\text{O}_2] - [\text{NO}_3^-])$  and sedimentary denitrification rate, each applicable across a given range of  $([\text{O}_2] - [\text{NO}_3^-])$  values (Figure S1). Due to the nature of our linear model, we needed to express the interval cutoff points that define the transition between the piecewise relationship segments in terms of  $\text{O}_2$  rather than  $([\text{O}_2] - [\text{NO}_3^-])$ .”
- Page 13, line 21: Sentence has been rephrased to indicate that there are 200,160 total ocean boxes in the model.
  - Added text: “All model ocean boxes (200,160 in total) are accounted for in the matrices.”
- Page 17, line 27: Rephrased as requested.
- Page 17, lines 21-31: This section of text refers to model nitrate  $\delta^{15}\text{N}$  that is lower than observations on a transect extending westward from the ETSP oxygen deficient zone, which we propose to be due to an underestimate of  $\text{NO}_3^-$  reduction in the model ETSP. We interpret the reviewer’s question to be about the potential role of fractionation during  $\text{NH}_4^+$  production and consumption in driving  $\text{NO}_3^-$  isotope variations in the real ocean, which are not fully represented in the model. We agree that there typically are large fractionation factors associated with usage of  $\text{NH}_4^+$  via uptake or oxidation, and that these fractionation factors should be expressed if  $\text{NH}_4^+$  accumulates in the water

column, or if there is a large difference in fractionation factors between competing pathways. The reviewer rightly points out that  $\text{NH}_4^+$  is not explicitly included in the model. We feel justified in doing this since accumulation of  $\text{NH}_4^+$  in the modern ocean, even in oxygen deficient zones, is typically very low. We agree that ignoring  $\text{NH}_4^+$  in euxinic conditions, where it constitutes a large fraction of dissolved inorganic N, would not be advisable. In the current model, while not explicitly representing  $\text{NH}_4^+$  as a DIN species, we do attempt to represent the partitioning of  $\text{NH}_4^+$  generated during DON degradation (ammonification) between ammonia oxidation and anammox below the euphotic zone. From an isotope balance perspective, we also assume that these competing fates have similar fractionation factors, which, while fairly uncertain, is generally supported by available data. Here we apply similarly *low* fractionation factors ( $\alpha = 1$ ), which is not likely the case, but turns out to not impact nitrate  $\delta^{15}\text{N}$  in the circumstances applied here, where  $\text{NH}_4^+$  does not accumulate, and both consumption processes have the same isotope effect. As applied here, the  $\text{NO}_3^-$  generated has the same  $\delta^{15}\text{N}$  as remineralized DON. If an isotope effect were applied to ammonia oxidation, this would most likely lower the  $\delta^{15}\text{N}$  of nitrate, not raise it. We believe that if anything our model results are biased towards the upper limit of nitrate  $\delta^{15}\text{N}$  produced during nitrification. One scenario of concern for our application would be if anammox has a much larger fractionation factor towards  $\text{NH}_4^+$  than ammonia oxidation, leaving  $^{15}\text{N}$ -enriched  $\text{NH}_4^+$  to be oxidized to  $\text{NO}_3^-$  in the water column. While theoretically possible, there are no observations that we are aware of that would support this scenario in the modern ocean. Secondly, if partly consumed  $\text{NH}_4^+$  is released from the sediments and oxidized to  $\text{NO}_3^-$  in the water column this could contribute to  $^{15}\text{N}$ -enrichment of  $\text{NO}_3^-$  that is not represented by the model. There is observational support for this effect in the modern ocean, as mentioned by reviewer #2. In response to these two questions about the underrepresentation of  $\text{NH}_4^+$  in the model, we have added a few additional comments regarding potential errors in the model associated with our representation.

- Added text:

- p. 13: “This is a conservative estimate of the effects of benthic N loss on water column  $\text{NO}_3^-$  isotopes, as several studies suggest that benthic N processes may contribute to water column nitrate  $^{15}\text{N}$ -enrichment (Lehmann et al., 2007; Granger et al., 2011; Somes et al., 2015; Brown et al., 2015). However, our current model parameterization does not require additional benthic fractionation to fit deep ocean  $\delta^{15}\text{N}_{\text{NO}_3}$ . Also, our spatial resolution does not well represent regions where this effect might be important.”
- p. 18: “The simplification of  $\text{NH}_4^+$  dynamics in the model could contribute to underestimation of  $\delta^{15}\text{N}_{\text{NO}_3}$  values if there were a large flux of  $^{15}\text{N}$ -enriched  $\text{NH}_4^+$  from sediments (Granger et al., 2011), or if  $^{15}\text{N}$ -depleted  $\text{NH}_4^+$  was preferentially transferred to the  $\text{N}_2$  pool via anammox. While the isotope effect on  $\text{NH}_4^+$  during anammox (Brunner et al., 2013) is higher than that applied here, we chose to balance this with a low isotope effect during aerobic  $\text{NH}_4^+$  oxidation (Table 1).”

- Page 19, line 25: These sentences have been reworked to indicate that low  $\text{NO}_2^-$  consumption rates (via NIR, AMX, and NXR) in conjunction with modest  $\text{NO}_2^-$  production rates (via NAR and likely AMO) result in an accumulation of  $\text{NO}_2^-$ .
  - Added text: “The accumulation of  $\text{NO}_2^-$  here in the model is likely due to  $\text{O}_2$  concentrations falling below the set threshold for NAR but above the threshold for NIR, so  $\text{NO}_2^-$  can accumulate via NAR but cannot be consumed via NIR. Although AMX and NXR occur there, the modeled rates of their  $\text{NO}_2^-$  consumption are rather low, which in combination with high rates of NAR and no NIR leads to more  $\text{NO}_2^-$  being produced than consumed.”
- Page 20, line 14: Acronyms have been replaced with full process names in the conclusion.
- Figure 4: The figure has been amended to include a color legend for clarity (see attached image).