

## Response to Reviewer 2

Thank you for your review.

- Page 3, lines 2-5: It is likely that the isotope effects measurements are subject to both environmental conditions and the microbial community composition. Though the strains chosen for culture by Buchwald and Casciotti (2010) and Casciotti (2009) are thought to be representative of the marine nitrite oxidizing community, that is not necessarily the case, and the pure culture studies in the laboratory are missing potential feedbacks from other *in situ* microbial processes or changing environmental conditions on an extremely local scale. There has been evidence for changing isotope effect expression under different environmental conditions (e.g. Kritee et al., 2012), so that could play a role in the different estimates. It is also possible that nitrite oxidation could be occurring with an alternative electron acceptor, but would be difficult to incorporate into our model due to our lack of thorough understanding about what these alternative pathways might be.
- Page 4, line 20: It would be a considerable computational challenge to increase the resolution of the physical circulation model. The data assimilation process used to construct the data-constrained tracer-transport model used in the present study took more than 1 month on a dedicated computer. With an increase in the horizontal resolution to  $\sim 1/2^\circ$  (the minimum resolution needed to start resolving the coastal ocean) the computational cost per iteration would increase by a factor of 16 and a larger number of iterations would likely be needed for the optimization to converge. Furthermore, the direct matrix inversions which we use to solve the physical and biogeochemical models would no longer be possible. The memory requirements would be too high. As a result, the fast direct solvers would have to be replaced by slower iterative solvers. Thus a global inverse model that resolves the coastal oceans is not presently feasible. It should however be feasible to embed our biogeochemistry model into a regional physical circulation model that resolves the coastal circulation.
- Page 4, lines 30-32: 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 5, line 23: A definition for the World Ocean Atlas acronym has been added to its first usage.
- Page 5, lines 28-30 and page 6, lines 1-2: DON in the model is not differentiated between labile and recalcitrant pools. The concentrations at the surface are largely between 0-20  $\mu\text{M}$ , with some higher concentrations in equatorial regions with high surface production. The DON concentration decays rapidly with depth, as its distribution is controlled by PON solubilization (driven by a Martin curve) and remineralization with a first order rate constant. Though the concentration in the surface box is higher than it should be, averaging the concentration over the top two or three boxes (representative of the mixed layer) yields concentrations closer to 10  $\mu\text{M}$ . The representation of ON in

the model and the surface processes that affect it is relatively simplified, and could be improved and expanded in subsequent versions of the model.

- Page 6, line 9: The modeled N deposition values here match observations fairly well (see Dentener et al., 2006) though there is some spatial variation in the goodness of the prediction. Many of the regions with lower prediction accuracy are also those with lower fluxes, so the errors do not lead to large under- or over-predictions for global N deposition. There are some newer estimates for N deposition (as well as future projections) that will be explored in a subsequent paper.
- Page 6, lines 25-28 and page 7, lines 1-2: Though our N<sub>2</sub> fixation parameterization is by no means perfect, we do not exclude non-*Trichodesmium* N<sub>2</sub> fixers. Explicitly adding additional types of N<sub>2</sub> fixers would require different parameters for maximum N<sub>2</sub> fixation rate, temperature constraints, and Fe and PO<sub>4</sub><sup>3-</sup> limitation, which we do not have good literature values for and are limited computationally by the number of parameters we can optimize. Additional investigations using this model that focus more on N<sub>2</sub> fixation rates could certainly implement different classes of N<sub>2</sub> fixers, but the generally good spatial patterns of N<sub>2</sub> fixation in the model and appropriate global rates (see below) are adequate for the ODZ analyses of interest here.
- Page 7, lines 12-13: The spatial patterns of N<sub>2</sub> fixation produced by the model are very similar to the observationally-constrained estimates of Luo et al. (2014). The modeled rates of N<sub>2</sub> fixation are appropriately low in the ETSP. Another paper (submitted to Global Biogeochemical Cycles) focuses on assessment of the N cycle process rates and their comparison to both other models and observational data.
- Page 8, lines 6-7: We believe that this is a reasonable assumption within the coarse framework of our model. Assimilation is only represented in the top two boxes of the model, which extend from 0-36 m (box 1) and 36-73 m (box 2). These two boxes are shallower than the characteristic high accumulation of NO<sub>2</sub><sup>-</sup> in the oxygen deficient zone, and accumulation of NO<sub>2</sub><sup>-</sup> in the primary NO<sub>2</sub><sup>-</sup> maximum usually only reaches a maximum of 1-2 μM, which would be negligible compared to NO<sub>3</sub><sup>-</sup>.
- Page 8, lines 30-31: Though carbon burial is higher under anoxic conditions, there have been other work that has shown preferential mineralization of N relative to C under anoxic conditions (e.g. Van Mooy et al., 2002; Roberts et al., 2012). Since variable C:N ratios are beyond the scope of this model, and in order to keep things simple, we assume that the preferential mineralization of N relative to C balances the slower mineralization rate under anoxic conditions.
- Page 10, lines 14-15: We have revised this section to note that our estimate of denitrification does not include chemoautotrophic denitrification, citing Lavik et al., 2009. As our model does not include cycling of reduced sulfur species, it is not possible for us to include chemoautotrophic denitrification at this time, leading to our estimates potentially underestimating overall rates of denitrification. However, since our model is optimized to fit observations of NO<sub>3</sub><sup>-</sup> and NO<sub>2</sub><sup>-</sup> concentration and isotopes, the overall rate of denitrification is constrained. If chemolithotrophic denitrification can be assumed to have a similar N isotope effect as heterotrophic denitrification (Frey et al., 2014), it may just be part of the mix of our signal.

- Added text: “When NAR occurs chemoautotrophically, it would be dependent primarily on the presence of  $\text{NO}_3^-$  and an electron donor, such as hydrogen sulfide (Lavik et al., 2009). Since we do not model the production of reduced sulfur species in our model, our estimates of denitrification would not explicitly include the effects of this process. However, chemolithotrophic denitrification could be tacitly accounted for in the optimization process, since the rate constants that control the rates of NAR and NIR are optimized in order to best fit the observations, and the isotope effect for chemolithotrophic denitrification is thought to be similar to that of heterotrophic denitrification (Frey et al., 2014).”
- Page 11, line 1: If the thresholds were set to nanomolar levels as suggested by Dalsgaard et al. (2014), there would be virtually no NAR, NIR, or AMX occurring in the model at all. The coarse resolution of the model results in depth-averaged  $[\text{O}_2]$  in many ODZ boxes that are above zero, even after applying the empirical correction put forward by Bianchi et al. (2012) to improve WOA  $\text{O}_2$  data fit in ODZs. It is not possible in this coarse, time-independent scheme to model any truly anoxic microenvironments. As a result, the area of the model ocean which is truly anoxic is very small. The area in which NAR, NIR, and AMX have been measured, observed, inferred, and modeled in previous ODZ studies is much greater than the extent of the anoxic model boxes, and thus we have chosen to be more flexible in our  $\text{O}_2$  thresholds for anoxic processes in order to best reflect current knowledge of what is occurring within ODZs. As discussed in Section 4.2, the model dependency on this input  $\text{O}_2$  has its downsides and does not adequately represent all ODZs despite our accommodating thresholds. The  $\text{O}_2$  thresholds and the effect of changing the thresholds on process rates is discussed further in another paper (submitted to Global Biogeochemical Cycles).
- Page 11, line 13: Previous studies on the biomechanics of anammox have included the nitrate oxidoreductase enzyme, as the oxidation of nitrite via this enzyme produced electrons that are needed for autotrophic  $\text{CO}_2$  fixation under normal anammox conditions (de Almeida et al., 2011; Kartal and Keltjens, 2016). Culture studies have also measured the stoichiometric production of  $\text{NO}_3^-$ , presumably by this enzyme (Strous et al., 1999; Brunner et al., 2013).
- Page 12, lines 10-13: This is an excellent suggestion, which we appreciate. We have thought about how to address this in the paper, as unfortunately it is not possible in the scope of the current model to incorporate this process in the model. The quoted text below represents our revisions to the paper in accordance.
  - 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  $\delta^{15}\text{N}_{\text{NO}_3}$ . Additionally, our spatial resolution does not well represent regions where this effect might be significant on bottom water  $\delta^{15}\text{N}_{\text{NO}_3}$ , such as the shallow shelves.”

- 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 14, lines 9-10: This paper has been submitted to Biogeosciences Discussions and will be available for proper citation shortly.
- Page 15, lines 22-25: The significance of these relationships was not calculated, and the lines shown are simply 1:1 lines to aid visual comparison between the modeled and observed data in the test set. It is likely that calculating such values would result in strange regression data and low significance. In many cases (particularly for  $\text{NO}_2^-$ ), the magnitude of the model is incorrect, but observing  $[\text{NO}_2^-]$  and  $\delta^{15}\text{N}_{\text{NO}_2}$  in a profile or section view reveals that the overall patterns are correct.
- Page 16, lines 17-18: The model cannot resolve episodic events, since it is a steady state, time-independent model that relies on a generalized circulation matrix. Though in the ETSP there is likely some upwelling that is incorporated into the circulation matrix, the more nuanced, time-dependent changes that occur in N cycling as a result of upwelling cannot be accounted for in this model.
  - Added text: “This could be due in part to the time-independent nature of this steady state inverse model, which does not capture the effects of upwelling events in the ETSP on N supply and cycling.”
- Page 16, lines 20-23: An additional line accounting for the impact of sedimentary  $\text{PO}_4^{3-}$  release on  $\text{N}^*$  has been added, though attempting to account for said release is beyond the capabilities of this model. This is particularly true since the shallow shelves where low  $\text{O}_2$  waters come into contact with sediments are not resolved in the model.
  - Added text: “Negative  $\text{N}^*$  values are associated with N loss due to AMX or NIR or release of  $\text{PO}_4^{3-}$  from anoxic sediments (Noffke et al., 2012), while positive  $\text{N}^*$  values are associated with input of new N through  $\text{N}_2$  fixation (Gruber and Sarmiento, 1997).”
- Page 17, line 2: It is not surprising that the model does not reproduce the high  $\delta^{15}\text{N}_{\text{NO}_3}$  values observed in the eddy for two reasons. First, the ETSP processes are not well-resolved by the model due to the aforementioned  $\text{O}_2$  threshold issues. Second, the time-independent and steady-state nature of the model would not be able to capture transient features such as eddies, where the  $\delta^{15}\text{N}_{\text{NO}_3}$  increases over time due to lack of  $\text{NO}_3^-$  resupply within the closed system of the eddy.
- Page 19, lines 2-3: This section has been rephrased. The original intent was to indicate the small fractional offset between the DIN and organic N model runs, both locally and globally.
  - Added text: “However, the majority of DIN assimilation estimates were within 10  $\mu\text{M}/\text{yr}$  of the organic N production estimates, with an average offset of approximately 3.5% compared to DIN assimilation. The total global assimilation

rates were within 0.4%, with some spatially variable differences due to offset between surface  $[\text{NO}_3^-]$  and modeled  $[\text{NO}_3^-]$ . However we find that the WOA surface  $\text{NO}_3^-$  values are fairly well represented by our modeled surface  $\text{NO}_3^-$  (Figure S4).“

- Page 19, lines 8-21: The  $\text{O}_2$  data product available through WOA is imperfect and coarse, which is why  $\text{O}_2$  thresholds have been adjusted to accommodate the values. The empirical correction calculated by Bianchi et al. (2012) that corrects the WOA using the GLODAP data attempts to tackle this issue, but the  $\text{O}_2$  values in ODZs are still too high. It is likely that if we had more thorough spatial coverage of  $\text{O}_2$  data from STOX sensors (rather than Seabird), we could use the model to more accurately and thoroughly probe some of the questions about  $\text{O}_2$  limitation for these processes. However, using a time-independent, steady-state model would still be unable to capture small, dynamic changes in  $\text{O}_2$  that may be important for driving some N cycling within regions that are close to the  $\text{O}_2$  detection limit or the  $\text{O}_2$  limit for these processes.
- Page 20, lines 12-13: Additional reference to Bourbonnais et al. (2015) has been added.
- Figure 3: The lines shown are not regressions, they are 1:1 lines and do not have associated  $r^2$  or significance values. See above for further discussion of the comparison between model output and test set data.
- Figure 4: These are indeed offshore profiles. Due to low model resolution, there are very few coastal or on-shelf boxes, especially in ODZs. A note has been added to the figure legend and description to indicate that the profiles are offshore.
- Figure 5-6: Section profiles comparing the modeled and observed  $[\text{NO}_2^-]$  and  $\delta^{15}\text{N}_{\text{NO}_2}$  for the GP16 transect have been added to the supplement (and are attached to this comment).  $\text{NO}_2^-$  does not accumulate along the GA03 transect and no  $\delta^{15}\text{N}_{\text{NO}_2}$  measurements were made, so those profiles are not included.
- Page 9, line 15: This font error and a few others were corrected.
- Page 21, line 8: This grammatical error was corrected.