Review of Rixen et al.

General comment

The manuscript by Rixen et al. gives a good overview of the development of OMZs and recent trends in the Arabian Sea and the Bay of Bengal, and discusses impacts from ocean circulation, export production and mesoscale eddies. The paper also reviews past and potential future OMZ strength as inferred from the sediment $\delta^{15}N$ and model predictions and looks at the pelagic and benthic ecosystem responses.
The paper is generally sound and has the potential to present a much needed comprehensive review of the Arabian Sea OMZs. It is however, quite apparent that the different sections were written by different authors as the writing style and the transitions from one section to another are incongruent. The manuscript should be at least partially rewritten to improve the flow. Some sections clearly need editing by an native English speaker (in particular the abstract, introduction, and conclusion). Some sentences are unclear or repetitive. I found several typos through the manuscript. See my technical corrections below for some suggestions on how to improve these sections.
On another note, the adopted O_2 thresholds defining hypoxia and anoxia are confusing. Several papers use a much higher O_2 threshold to define hypoxia (e.g., >63 μM, Vaquer-Sunyer and Duarte, 2008 and reference therein). The presence of H_2S should rather be referred to as sulfidic conditions, as sulfate reduction does not necessarily occur under anoxic conditions. A clear distinction between Oxygen Minimum Zones (OMZs) and Oxygen Deficient Zones (ODZs) should also be made.
Finally, some figures should be added or improved for clarity. For instance, a figure explaining the development of an OMZ in relation to ocean circulation and seasonal monsoons would be helpful (Background, section 2.2).

Specific comments:

Abstract:

Overall, the whole abstract ought to be rewritten to summarize the main points of the manuscript. The current version is confusing, and at times vague. Also, the abstract should follow a more logical order following the order of the different sections as presented in the text.

Line 4: Nitrate loss is only a problem if it is limiting (i.e., in a non-eutrophic system).

Lines 14-16: This sentence is confusing and needs clarification. It should be rephrased to emphasize that, based on previous studies (e.g., Aumont *et al.*, 2015), decreasing oxygen concentration slows down respiration and thus decreases oxygen demand. The following sentence is also unclear as it is.

Lines 19-21: This sentence is too vague. Effects on benthic and pelagic ecosystems should be better summarized.

Introduction

Lines 27-30: This sentence is ambiguously worded.

Lines 30-32: N_2O is also produced as an intermediate during denitrification and is a by-product of nitrification. N_2O is a greenhouse gas 300 times more potent than CO_2 and an ozone destructing substance and should also be included here.

Lines 46-48: The availability and quality (organic matter stoichiometry) of organic material is a key control on denitrification versus anammox (Babbin *et al.*, 2014).

Lines 60-61: Their definitiona of hypoxia and anoxia are a bit confusing since most studies define hypoxia at O_2 concentrations >63 μM (Vaquer-Sunyer and Duarte, 2008 and reference therein). Anoxia (O_2 concentrations close to zero or in the nmol range) can also occur without hydrogen sulfide production.

Lines 66-67: I don't quite understand this sentence. Marine ecosystem services need to be defined earlier in the text. I suggest removing this sentence as the next sentence (lines 67-70) articulates the same idea better.

Lines 80-82: The more recent estimates by Eugster and Gruber (2014) of 52 Tg N yr^{-1} for water column denitrification and 93 Tg N yr^{-1} for benthic denitrification should be referenced. The distinction between water column and benthic rates should be made more explicitly.

Lines 84-85: Considering a mean sedimentary denitrification rate by Eugster and Gruber (2014) of 93 Tg N yr^{-1}, the proportion of sedimentary denitrification at the Pakistan continental margin could be even higher.

Main text

Lines 124-151: A figure showing the impact of ocean circulation in relation to seasonal monsoon on OMZ expansion in the eastern and western Arabian Sea would be helpful.

Lines 144-146: Is this low areal extension associated with increased thickness of the ODZ, as shown in Figure 4? This should be clarified here.

Lines 166-168: Why this ballast-effect mostly occurring in the Bay of Bengal and not the Arabian Sea?

Lines 180-182: A distinction should be made between human-induced coastal eutrophication and coastal dead zone development due to the imbalance between higher O_2 consumption from primary productivity (upwelling) relative to O_2 supply from physical circulation.

Lines 198-199: A reference is needed to support this O_2 threshold.

Lines 191-193: How does the relatively low denitrification rate estimated by Bristow *et al*. (2017) compares to the denitrification rate (including anammox) measured in the Arabian Sea using ^{15}N-labeled incubations by Ward *et al.* (2009)?

Lines 215-217: This is an important point that should be described better in the abstract.

Line 229: The term (central Indian Ocean) is already defined in the previous section.

Lines 267-268: I don't quite understand this sentence either. Do they mean in contrast to the upper part of the SNM?

Lines 277-279: How does figure 3 support this point?

Lines 319-323: The roles of coastal mode water anticyclonic eddies as N-loss hotspot in the Peru upwelling system should also be referenced (Bourbonnais *et al*., 2015; Altabet and Bourbonnais, 2019). The paper by Fassbender *et al.* (2018) also provides a good review of the effects of mesoscale and submesoscale features on ocean biogeochemistry.

Lines 339-342: On which timescale are these feedbacks expected to occur?

Lines 379-381: These two terms "eddy-driven isopycnal tracer mixing" and "isopycnal flattening" need to be explained.

Lines 419-420: The authors should be more specific about which results they are referring to (Bristow *et al*., 2017).

Line 471: A reference is needed to support this O_2 threshold for denitrification. Dalsgaard *et al.* (2014) report an O_2 threshold in the nmol range for denitrification.

Lines 486-488: The model's results do not seems to support denitrification during the Holocene.

Lines 497-498: Was a relationship between orbital forcing (i.e., Milankovitch cycles) and the development of the OMZ ever investigated in the region? A reference should be added.

Lines 515-519: Submesoscale processes, which are ephemeral and take place over lengths of about 1-10 km lasting several days, are also poorly represented (see Fassbender *et al*., 2018).

Lines 600-616: What is the effect of these larges blooms on OMZ expansion?

Lines 702-705 and 715-720: At which oxygen thresholds are these community composition and faunal abundance changes observed?

Lines 745-748: What is the N:P ratio in the overlying ODZ versus the sediments? Lower N:P ratios than expected based on NO_3^- loss and biogenic N_2 production during denitrification are often observed in coastal ODZs due to the preferential release of PO_4^{3-} following iron and manganese oxyhydroxide dissolution in anoxic sediments (Noffke *et al*., 2012).

Line 750: Define "dark" carbon.

Lines 797-800: Higher oxygen concentrations are more likely the results of the development of a sharper pycnocline (from higher freshwater fluxes) and lower primary productivity in the Bay of Bengal.

Conclusion:

Lines 800-802: This sentence is unclear. Do they mean that mesoscale eddies sustain higher O_2 concentrations in the OMZ than expected in their absence?

Figures: AOU should be showed instead of Δoxygen (μmol kg^{-1}) in this figure since this is what is discussed in the text. Something must be wrong with the scale for Δoxygen (μmol kg^{-1}). The Δoxygen (deviation from O_2 concentrations at saturation) should be much higher than 10 μmol kg^{-1} to cause hypoxic/anoxic conditions.
Why is the figure broken into two panels (a, b)? Another suggestion is the break the axis for depth >500 m.

Figure 4. It is unclear how to reconcile data in Figure 2 - showing that overall a decrease in the OMZ area seems to correspond to a decrease in the mean OMZ oxygen concentrations (at least during summer monsoon when POC flux is highest) and Figure 4 - showing a negative correlation between OMZ max thickness and the mean OMZ oxygen concentration.

Figure 5. This figure is difficult to read (white font on light blue background). Font size should be bigger. Isopycnal mixing by mesoscale eddies could be emphasized in a.

Figure 6. Make d as a symbol (y axis): "$\delta^{15}N$"

Technical corrections:

Line 4: Change "increases the loss nitrate" to "increases nitrate loss"

Lines 4-5: Change to "Nitrate is a macronutrient limiting primary productivity in most of the ocean."

Lines 7-10: This sentence seems to be out of context and repetitive considering the following sentence. I suggest rewriting:
"The main control on oxygen concentrations in the Arabian Sea and the Bay of Bengal is the balance between physical oxygen supply and biological oxygen consumption from respiration. Mesoscale eddies greatly enhance mixing and advection of O_2-rich waters, which compensate biological consumption and overall reduces ODZ expansion."

Lines 12-14: Change to: "However, due to slightly higher oxygen concentrations, aerobic nitrite oxidation outcompete anaerobic nitrite reduction and thus limits denitrification in the Bay of Bengal"

Line 39: Replace "At" with "Under" at the beginning of sentence.

Lines 62 and 64 and 806: Change "hyp-" for hypoxic here and everywhere else in the text.

Line 74: Remove "is": "..., with a much smaller proportion ~~is~~ located in the Bay of Bengal..."

Line 83: Replace "to this data" with "published data".

Line 90: Change to: "one of the least understood OMZs"

Line 183: Replace "conational" for "continental"

Line 190: Replace "nitrite oxidization" with "nitrite oxidation"

Line 201: Replace "this is with about 0.7 μM much higher" by "it is about 0.7 μM higher".

Line 202: Remove the at beginning of sentence: "However, ~~the~~ in comparison to the Arabian Sea..." and remove "as in the Arabian Sea" at the end of sentence.

Lines 208-209: Replace with: "Subsequent studies also reported decreasing oxygen concentrations in the western and northern Arabian Sea."

Line 255: Replace with: "in the upper part <u>of the</u> seasonal thermocline..."

Line 258: Replace "stabile" with "stable"

Line 270: Replace "SNN" with "SNM"

Lines 279-281: Therewith is used twice within the same sentence.

Line 286: Remove "in": "... is mostly remineralized within ~~in~~ the upper 300 m..."

Line 292: Remove "also"

Line 297: Replace "the hypothesis" by "this hypothesis"

Line 439: This term (ICW) is already defined earlier in the text.

Lines 534 and 539: Change for 80 μM $\underline{O_2}$ and 50 μM $\underline{O_2}$.

Line 573: Replace for: "... can survive at O_2 concentrations down to 4.5 μM"

Line 593: Remove one "waters": "... nutrient-enriched ~~waters~~ subsurface waters..."

Line 617: Add a space after Gomes *et al.* (2014).

Line 630: Remove one "of": "... the capacity of the ~~of~~ endosymbionts..."

Line 685: Replace with: "... will have implications for the cycling <u>of</u> nutrients and oxygen..."

Line 797: Change to:"... to a degree that ~~is~~ prevented denitrification..."

Lines 797: Start new sentence with "In": "~~The~~ In comparison to the..."

Additional references:

Altabet, M. A., & Bourbonnais, A. (2019). N-loss stoichiometry in a Peru ODZ eddy. *Journal of Marine Research*, *77*(2), 169-189.

Babbin, A. R., Keil, R. G., Devol, A. H., & Ward, B. B. (2014). Organic matter stoichiometry, flux, and oxygen control nitrogen loss in the ocean. *Science*, *344*(6182), 406-408.

Bourbonnais, A., Altabet, M. A., Charoenpong, C. N., Larkum, J., Hu, H., Bange, H. W., & Stramma, L. (2015). N-loss isotope effects in the Peru oxygen minimum zone studied using a mesoscale eddy as a natural tracer experiment. *Global Biogeochemical Cycles*, *29*(6), 793-811.

Eugster, O., & Gruber, N. (2012). A probabilistic estimate of global marine N-fixation and denitrification. *Global Biogeochemical Cycles*, *26*(4).

Fassbender, A. J., Bourbonnais, A., Clayton, S., Gaube, P., Omand, M., Franks, P. J. S., ... & McGillicuddy Jr, D. (2018). Interpreting mosaics of ocean biogeochemistry. *Eos*, *99*(10.1029).

Noffke, A., Hensen, C., Sommer, S., Scholz, F., Bohlen, L., Mosch, T., ... & Wallmann, K. (2012). Benthic iron and phosphorus fluxes across the Peruvian oxygen minimum zone. *Limnology and Oceanography*, *57*(3), 851-867.

Vaquer-Sunyer, R., & Duarte, C. M. (2008). Thresholds of hypoxia for marine biodiversity. *Proceedings of the National Academy of Sciences*, *105*(40), 15452-15457.