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Key Points:
- Remineralization depth plays an essential role in generating the observed contrast of low-oxygen waters and denitrification
- Contrasting distributions of oxygen and nitrate at depths can only be simulated using varying remineralization depth in the model
- Results support the hypothesis that organic matter aggregation with riverine particles contributes to OMZ contrasts in the Indian Ocean

Supporting Information:
- Supporting Information S1

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Oxygen Minimum Zone Contrasts Between the Arabian Sea and the Bay of Bengal Implied by Differences in Remineralization Depth

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Abstract The combination of high primary productivity and weak ventilation in the Arabian Sea (AS) and Bay of Bengal (BoB) generates vast areas of depleted oxygen, known as oxygen minimum zones (OMZs). The AS OMZ is the world's thickest and hosts up to 40% of global denitrification. In contrast, the OMZ in the BoB is weaker and denitrification free. Using a series of model simulations, we show that the deeper remineralization depth (RD) in the BoB, potentially associated with organic matter aggregation with riverine mineral particles, contributes to weaken its OMZ. When the RD is set uniformly across both seas, the model fails to reproduce the observed contrast between the two OMZs, irrespective of the chosen RD. In contrast, when the RD is allowed to vary spatially, the contrasting distributions of oxygen and nitrate are correctly reproduced, and water column denitrification is simulated exclusively in the AS, in agreement with observations.

1. Introduction

Nutrient supply to the ocean surface fuels biological productivity in the euphotic zone that induces an intense downward flux of organic matter. Decomposition (remineralization) of the exported organic matter consumes oxygen throughout the water column. In conjunction with the weak vertical and lateral ventilation that characterize the northern Indian and eastern tropical Atlantic and Pacific Oceans, the oxygen consumption at depths leads to large oxygen minimum zones (OMZs) in the intermediate ocean. Under very low-oxygen conditions (suboxia), nitrate is used as the alternate oxidant for the organic remineralization in a process known as denitrification. This not only depletes the pool of bioavailable nitrogen but also contributes to production of N_2O, a potent greenhouse gas to the atmosphere (Naqvi et al., 2010). This highlights the importance of the OMZs for the ocean nitrogen and carbon cycles, and for climate (Codispoti & Christensen, 1985; Thamdrup, 2011; Ward, 2013).

More than half of the area containing OMZs in the world ocean is located in the Arabian Sea (AS) and in the Bay of Bengal (BoB), in the northern Indian Ocean, but with a varying intensity between the two seas (Helly & Levin, 2004; Paulmier & Ruiz-Pino, 2009). The oxygen is depleted to suboxic level ($\leq$5 μM) over large swaths of the AS, inducing intense denitrification fluxes there. In contrast, the low-oxygen concentrations in the BoB remain above the suboxic levels, preventing large-scale denitrification from occurring (Howell et al., 1997). Reasons proposed for the contrast in OMZ intensity between the two seas include variations in levels of primary productivity, differing intensities of mesoscale eddies, and a contrasting transport of organic matter and oxygen (McCreary et al., 2013). However, no conclusive quantitative investigation of these factors has been made, nor have the mechanisms maintaining the contrast been elucidated. This is partly because modeling studies inadequately represent the observed intensity and structure of the OMZs in the AS and the BoB (Cabré et al., 2015; Cocco et al., 2013; Gnanadesikan et al., 2012; Oschlies et al., 2008).

Observations of vertical fluxes of particulate organic matter show that although primary productivity in the BoB is generally lower than in the AS, comparable or even higher deep-ocean organic fluxes are measured in the BoB relative to those in the central and eastern AS (Gauns et al., 2005; Ittekkot et al., 1991; Lutz et al., 2002). This has been suggested to result from the aggregation of organic matter with mineral particles from rivers in the BoB, which increases the sinking speed of the falling organic matter and reduces its remineralization rate by providing a protection that slows down its decomposition (Howell et al., 1997; Iversen & Ploug, 2010; Klaas & Archer, 2002; Le Moigne et al., 2013; Rao et al., 1994). Thus, in the BoB, the riverine mineral ballast potentially affects the remineralization depth, defined as the depth at which sinking organic matter is decomposed back to inorganic carbon and nutrients. This depth depends on the balance between the sinking speed and the rate of remineralization and characterizes the efficiency of the downward export of organic matter (Kwon et al., 2009; Rao et al., 1994). Because it affects the vertical profile of organic matter, the remineralization depth also affects the vertical profile of oxygen consumption and hence can impact the OMZ structure and intensity. However, its potential contribution to the OMZ differential intensity between the BoB and AS has not yet been explored.

Here we implement a coupled physical-biogeochemical regional ocean model to test and validate the hypothesis that differences in the remineralization depth between the AS and the BoB do contribute to the observed contrast in low-oxygen concentrations and occurrence of denitrification between the two seas. More specifically, our simulations show that the deeper remineralization depth in the BoB, potentially driven by stronger riverine input of mineral ballast, does contribute to weaken its OMZ and suppress denitrification there.

2. Methods

2.1. Model Description

Our circulation model is the Regional Ocean Modeling System—Agrif version 3.1.1 (http://www.romsagrif.org) (Shchepetkin & McWilliams, 2005). The biogeochemical model is a nitrogen-based nutrient-phytoplankton-zooplankton-detritus (NPZD) model including two nutrients (nitrate and ammonium) and two classes of detritus (small and large sizes) (Gruber et al., 2006). The model includes a representation of the oxygen cycle as well as a parameterization of water-column and benthic denitrification (Lachkar et al., 2016). The model domain covers the Indian Ocean from 31°S to 31°N and 30°E to 120°E (see Figures S1 in the supporting information). The model horizontal resolution is eddy-resolving (1/10°). Monthly river discharges and annual averaged nutrient concentration from 10 major rivers in the northern Indian Ocean are derived from a global hydrological model and available measurements (Bird et al., 2008; Dai & Trenberth, 2002; Krishna et al., 2016; Ramesh et al., 1995). Further details of the model setup are given in the supporting information. Our model experiments were run for 70 years with the first 65 years considered as the model spin-up. We used the last five years of model simulations for the analysis.

Our goal is to investigate the role of remineralization depth in generating and maintaining the contrast of low-oxygen waters and denitrification between the AS and the BoB. Here we define the remineralization depth Rd_D of a detritus pool D as follows:

$$Rd_D = W_D/R_D$$

where W_D and R_D refer to detritus sinking speed and remineralization rate, respectively.

Using a sinking speed of 1 m d^{-1} and a remineralization rate of 0.03 day^{-1} in all of the simulations, the remineralization depth of small detritus is very shallow and amounts to 33 m. Therefore, organic matter remineralization below the euphotic zone is almost exclusively associated with large detritus. Thus, we restrict our sensitivity study to effects of remineralization depth of large detritus Rd_{LD} defined as follows:

$$Rd_{LD} = W_{LD}/R_{LD}$$

where W_{LD} and R_{LD} refer to large detritus sinking speed and remineralization rate, respectively.

In a first simulation (referred to as DeepRem), we start with the standard values of sinking speed (10 m d^{-1}) and remineralization rate (0.01 day^{-1}) of large detritus used in Gruber et al. (2006), corresponding to a remineralization depth of 1,000 m. In a second simulation (referred to as ShallowRem1), we reduce the remineralization depth to 500 m by decreasing the sinking speed to 5 m d^{-1} relative to that of the DeepRem simulation. In both simulations, the remineralization depth can locally increase in suboxic regions due to a 50% slower remineralization rate under denitrification (Lachkar et al., 2016). Yet this has a limited overall effect on the remineralization depth as it is restricted to areas at intermediate depths in the northeastern AS where denitrification is active. Finally, in a third simulation (VaryingRem1), we implement a parameterization of a varying remineralization depth that uses variations of sea surface salinity (SSS) to represent the effect of riverine influence on aggregation of organic matter with mineral particles in the BoB (see Table S1 in the supporting information).

2.2. Formulation for Varying Remineralization Depth

Observations of different material fluxes in the AS and the BoB from sediment traps (Haake et al., 1993; Ramaswamy et al., 1997; Ramaswamy & Nair, 1994; Unger et al., 2003) suggest that lithogenic fluxes, associated with terrigenous material from land, contribute substantially more to the total particulate fluxes in the BoB than in the AS. Indeed, the lithogenic fluxes provide up to 42% of the total fluxes in the BoB, while they only contribute to up to 25% of the total fluxes in the AS (Table S4 in the supporting information). Furthermore, the comparison with salinity observations reveals that the percentages of lithogenic fluxes vary inversely with the SSS in the BoB and the AS (Figure S8 in the supporting information). This suggests a direct influence of freshwater influx via its load of suspended lithogenic material on the particulate organic fluxes in the BoB. In particular, it is suggested that the large riverine input in this sea enhances the export efficiency by ballasting or protecting organic matter (Rao et al., 1994).

Here we assume the remineralization depth in the BoB to be approximately 3 times that of the AS based on previous estimates of water column decomposition rates made by Naqvi et al. (1996). The lower oxidation rates in the BoB were suggested to be linked with the protection of organic matter by rapidly sinking terrigenous matter (Naqvi et al., 1996). Following Murty et al. (1992), we use the isohaline of 34 practical salinity unit (psu) to mark the separation between the low salinity waters ($<$34 psu) influenced by the riverine freshwater influx in the Bay of Bengal and the more saline water in the Arabian Sea and elsewhere. Concretely, we set the remineralization depth Rd_{LD} to vary between 1,500 m if SSS $\leq$34.0 psu (mainly in the BoB) and 500 m if SSS $>$34.2 psu (elsewhere including the AS) by fixing the R_{LD} at 0.01 day^{-1} and varying W_{LD} in simulation VaryingRem1 as follows:

$$W_{LD} = \begin{cases} 15, \text{ if SSS} \leq 34{:}0 \\ 10, \text{ if } 34.0 < \text{SSS} \leq 34{:}2 \\ 5, \text{ if SSS} > 34.2 \end{cases}$$

2.3. Summary of Model Evaluation

The physical and biogeochemical model results are evaluated using available data from satellite and in situ measurements. The model, in general, reproduces the observed seasonal variation of sea surface temperature and salinity in the Indian Ocean (see Figures S2 and S3 in the supporting information), as well as the spatial distributions of mixed layer depth and eddy kinetic energy (Figures S4 and S5 in the supporting information). The model simulates relatively well the elevated net primary production (NPP) in the northern and western AS during winter and summer monsoon seasons, respectively, and the summer increase of the NPP in the BoB as shown by the satellite-based data, despite some local biases off the Somali coast and in the oligotrophic open ocean (Figure S6 in the supporting information). Furthermore, the observed general pattern of comparable or higher particulate organic flux but lower NPP in the BoB than in the central and eastern AS is well reproduced by the VaryingRem1 simulation (Figure S13 and Table S3 in the supporting information). Details of the model evaluation are provided in the supporting information.

Additional comparisons of modeled dissolved oxygen and nitrate with in situ observations highlighting the important role of remineralization depth are presented in detail in section 4. We focus on the annual-mean values because the seasonal variability of oxygen and nitrate in the intermediate waters is relatively weak (Resplandy et al., 2012). The observed oxygen is based on WOA13, with a correction to reduce biases associated with measured low-oxygen concentrations, following Bianchi et al. (2012) and Acharya and Panigrahi (2016).

3. Drivers of OMZ Intensity Contrasts

The NPP is substantially higher in the AS than in the BoB in all simulations (see Table S3 in the supporting information). At a first sight, this may appear consistent with the AS showing a more intense OMZ driven by a higher biological consumption of oxygen there. However, the contrast in NPP between the AS and the BoB does not correlate well with the differences in OMZ intensity between the two seas among the three simulations. In particular, the shallow remineralization simulation produces the strongest contrast in productivity between the two seas (+65% higher productivity in the AS), while also showing the weakest contrast in terms of the suboxic volume (see Figure 2). Indeed, in the shallow remineralization simulation the suboxic volume is only a factor 3 smaller in the BoB relative to the AS, whereas this difference is several times larger (more than a factor 20) in the case of the varying remineralization depth despite a weaker productivity contrast between the two seas in this simulation (+52% higher productivity in the AS). This lack of correlation, in our simulations, between productivity levels and the intensity of the OMZs in the two seas provides a strong indication that productivity differences alone cannot explain asymmetric low-oxygen distributions in the two seas.

Differences in ventilation between the AS and BoB can in principle contribute to the observed OMZ contrasts between the two seas. However, previous observational and modeling studies suggest that water mass residence times in the BoB are generally longer (12 years (Sarma, 2002b)) than in the AS (3–10 years (Howell et al., 1997) and 6.5 years (Sarma, 2002a)). This suggests weaker ventilation in the BoB, in comparison to the AS, and hence should act to weaken the observed OMZ intensity contrast between the two seas. Therefore, the ventilation difference appears also insufficient to explain the observed contrasts in oxygen levels as also suggested by Rao et al. (1994).

While the NPP controls the total concentration of sinking organic matter to be remineralized in each of the basins, the remineralization depth (regulated by remineralization rate and sinking speed) determines the vertical distributions of sinking organic matter along the water column, and hence the vertical distributions of oxygen and OMZ structure and intensity. Next, we explore the effect of varying remineralization depth on the OMZ intensity in the AS and the BoB.

4. Effect of Remineralization Depth on Low-Oxygen Waters and Denitrification

Our set of simulations highlights the importance of the remineralization depth in driving the intensity contrast of low-oxygen waters between the Arabian Sea (AS) and the Bay of Bengal (BoB) (Figure 1). In the DeepRem simulation, oxygen levels are overestimated in the AS, and the model is unable to reproduce the observed suboxic waters ($O_2 < 4$ mmol m^{-3}) there. On the other hand, modeled oxygen levels are relatively comparable with observations in the BoB (Figures 1c and 1d). In this simulation, the spatially uniform remineralization depth of 1,000 m tends to produce more flux of organic matter to deeper depths, thus depleting less oxygen in the intermediate depths of the AS, in comparison to observations (Figure 1d).

In the ShallowRem1 simulation, with a spatially uniform remineralization depth of 500 m, the observed suboxic water pool in the AS is better simulated (Figures 1e and 1f). The generally shallower remineralization depth in this simulation decreases the modeled flux of sinking organic matter to the deep ocean relative to the DeepRem simulation. As a consequence, more organic matter is decomposed in the intermediate waters, inducing higher oxygen consumption and leading to an intense OMZ in the AS that agrees well with observations. However, oxygen depletion in the BoB in this simulation is too strong and leads to an exaggeratedly intense OMZ, in contrast to the observations. Therefore, using either a deep or a shallow remineralization depth uniformly across the AS and the BoB results in a weakened contrast of the OMZ between the two seas.

On the other hand, we find that the contrast is well reproduced in the VaryingRem1 simulation, which exhibits a nonuniform remineralization depth of approximately 1,000 to 1,500 m in the BoB, where the modeled surface salinity is lower than 34 psu, and 500 m elsewhere, including the AS where higher salinities are found (Figures 1g and 1h). In this simulation, the model not only successfully produces the observed suboxic water in the AS but also maintains oxygen levels in the BoB above denitrification thresholds. This suggests that enhancement of the export efficiency in the BoB due to the riverine mineral ballast may potentially produce and maintain the observed oxygen intensity contrast between the two seas (Ittekkot et al., 1991; Rao et al., 1994).

A more quantitative analysis of the oxygen contrasts between the two seas is conducted by comparing the observed and simulated volume fraction of suboxic ($O_2 \leq 4$ mmol m^{-3}), hypoxic (4 mmol m^{-3} $< O_2 \leq$ 60 mmol m^{-3}), and oxic ($O_2 >$ 60 mmol m^{-3}) regions, following Lachkar et al. (2016) (Figure 2). The modeled suboxic volume is more sensitive to the change of the remineralization depth than the hypoxic and oxic volumes (Figure 2). In the DeepRem simulation, the simulated suboxic volume in the BoB is extremely small, in agreement with observations. Yet, in this simulation, the AS suboxic volume is approximately 3 times smaller than in the observations. Better agreement of the modeled suboxic volume with observations in the AS is obtained in

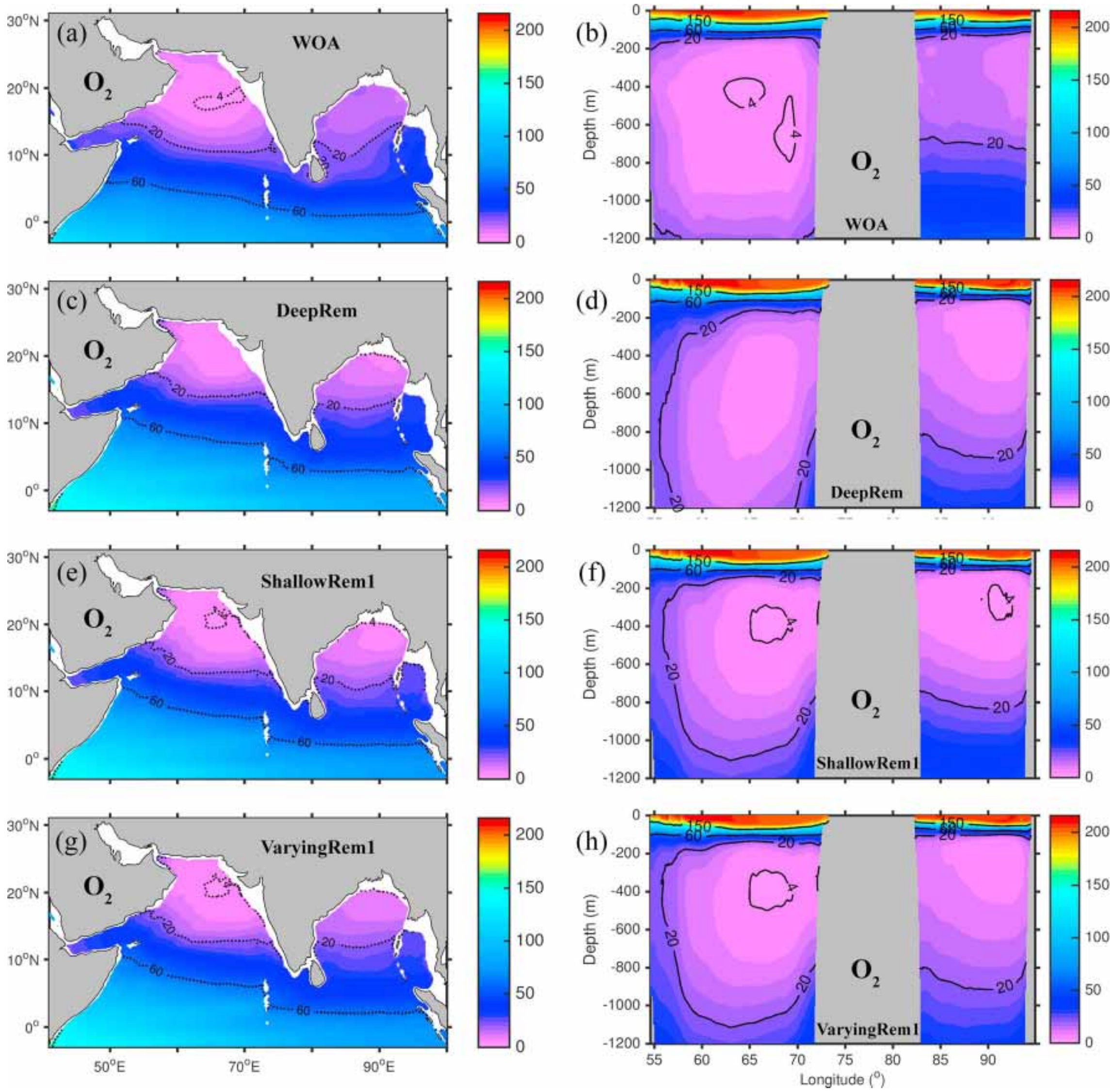

Figure 1. (left column) Vertically and (right column) meridionally averaged oxygen (mmol m^{-3}) from (a and b) observation and model results using (c and d) uniformly deep, (e and f) uniformly shallow, and (g and h) varying remineralization depths. The observation is from a corrected WOA13. The depth-averaged plots are averaged between 250 and 700 m. The zonal distributions are meridionally averaged between 16.5 and 20°N. The observed contrast of low oxygen between the AS and the BoB is well reproduced by the model with the varying remineralization depth (Figures 1g and 1h).

the ShallowRem1 simulation. This improvement in the AS comes nevertheless with a substantial degradation in the BoB, where the simulated suboxic volume is 10 times larger than in the observations (Figure 2). Finally, the model is able to reproduce well the volume of suboxia in both the AS and the BoB, as well as the observed contrast between the two seas, when we apply a nonuniform remineralization depth in the VaryingRem1 simulation that mimics the effect of aggregation of mineral ballast with organic matter in the BoB (Figure 2).

Improved model accuracy in reproducing the observed oxygen levels in the two seas also improves model accuracy in generating the contrast of active anaerobic remineralization through denitrification between the AS and BoB. An observed depth profile of denitrification rates from a station in the AS by Bulow et al. (2010) is relatively well reproduced in the ShallowRem1 simulation, which uses a spatially uniform shallow remineralization depth (Figure 3) despite an overestimation below 200 m. This overestimation may result from the fact that the observation is representative of conditions of a particular year (2007), whereas the model describes the long-term (climatological) conditions. The simplified representation of denitrification

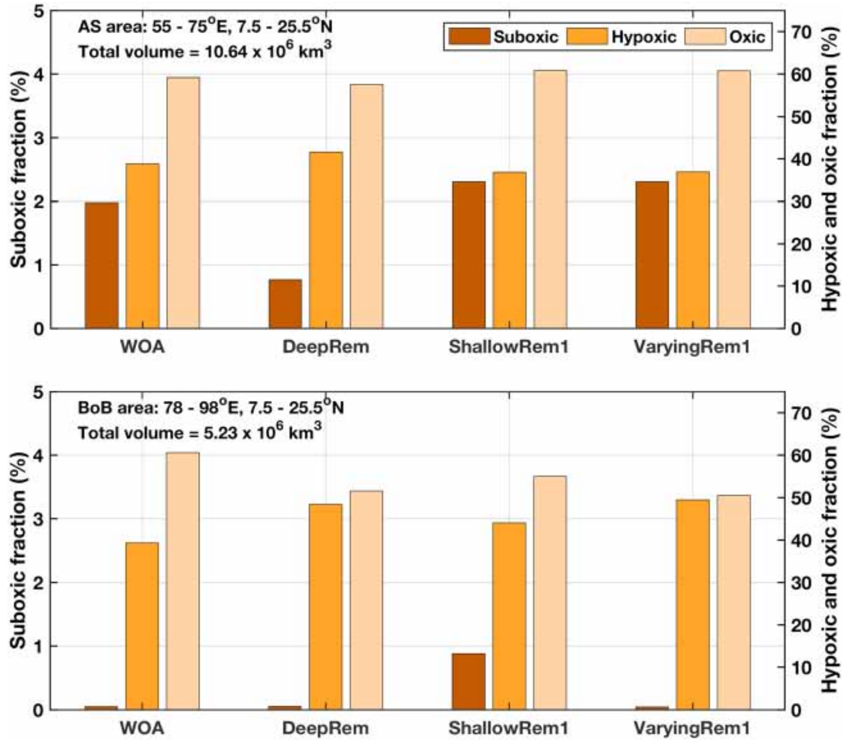

Figure 2. Observed and simulated volume fractions (%) of suboxic (left *y* axis), hypoxic and oxic (right *y* axis) waters in (top) the AS and (bottom) the BoB. $O_2 \leq 4$ is suboxic, $4 < O_2 \leq 60$ is hypoxic, and $O_2 > 60$ mmol m^{-3} is oxic waters. The observation is based on a corrected WOA13. The volume fractions are annually averaged and integrated over areas listed in this figure.

in the model as well as additional issues with the method of estimation of denitrification in the data could also contribute to the mismatch with the model (Bulow et al., 2010). Despite this bias, when averaged between 100 and 400 m, the modeled denitrification rate (6.9 ± 5.2 nmol L^{-1} d^{-1}) compares well with the observation (8.5 ± 2.7 nmol L^{-1} d^{-1}) at the AS station by Bulow et al. (2010). However, this simulation produces denitrification rates that are unrealistically high in the BoB (Figure 3). On the other hand, the DeepRem simulation that has deep remineralization everywhere reproduces well the observed extremely weak denitrification rates in the BoB, but this comes with a considerable underestimation of denitrification

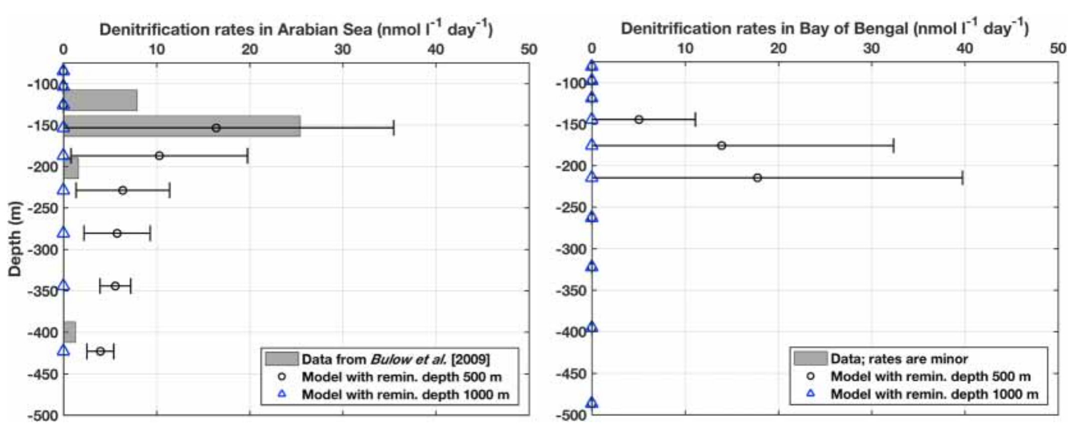

Figure 3. Measured and simulated denitrification rates in (left) the AS and (right) the BoB. The measured and modeled rates are averaged for September at a station at 66°E–19°N in the AS according to Bulow et al. (2010) and at 89°E–14°N in the BoB. The horizontal lines are temporal standard deviations, calculated for September over the last 5 years of the simulations.

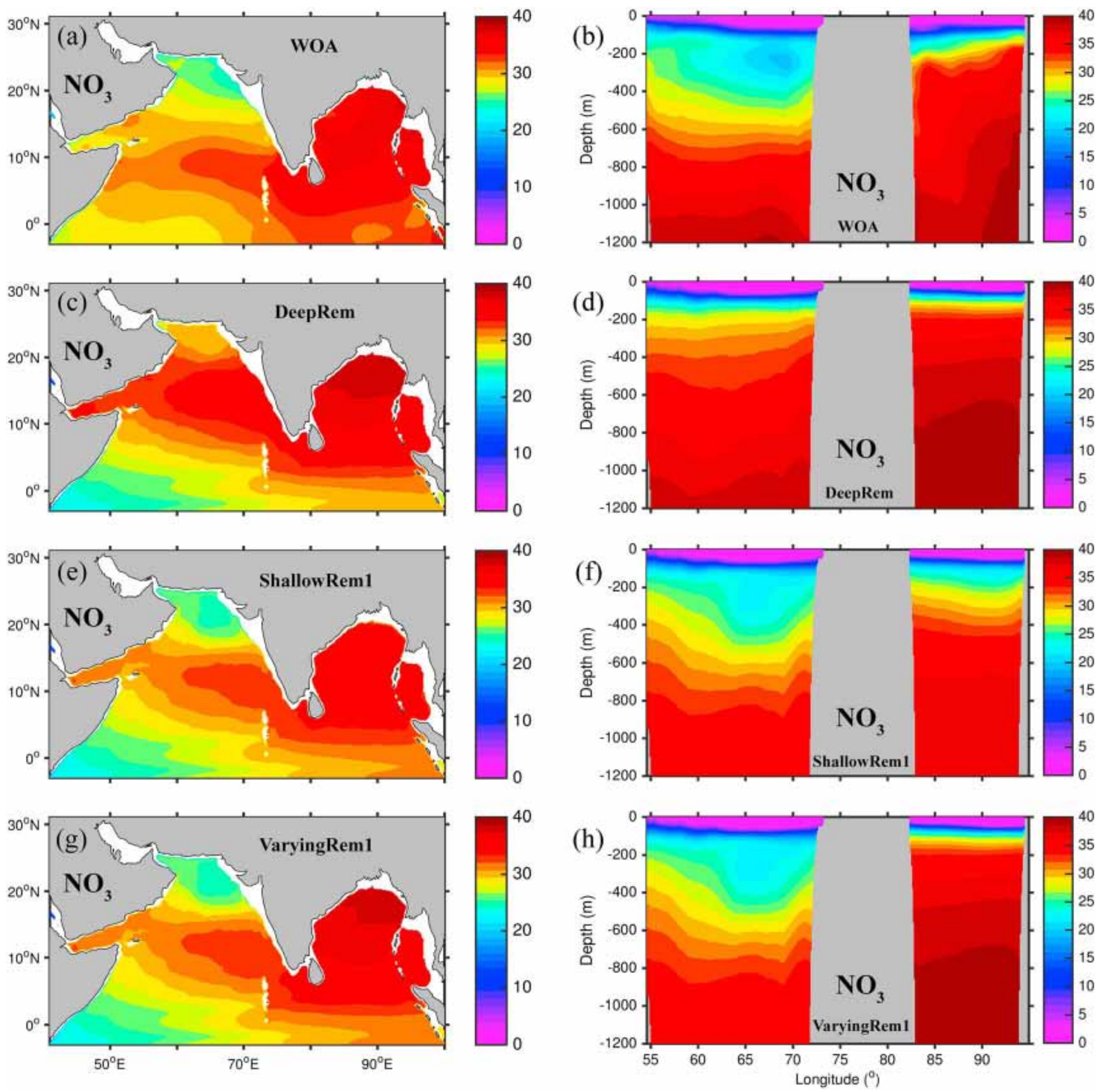

Figure 4. (left column) Vertically and (right column) meridionally averaged nitrate (mmol m^{-3}) from (a and b) observation and model results using (c and d) uniformly deep, (e and f) uniformly shallow, and (g and h) varying remineralization depths. The observation is obtained from WOA13. The depth-averaged plots are averaged between 250 and 700 m. The zonal distributions are meridionally averaged between 16.5 and 20°N. The active denitrification in the AS, but minor in the BoB are well reproduced by the model with varying remineralization depth (Figures 4g and 4h).

in the AS (Figure 3). The simulation with varying remineralization depth (VaryingRem1) results in similar denitrification rate as in the ShallowRem1 and DeepRem simulations for the AS and the BoB, respectively, in relative good agreement with the available observations.

Better-modeled denitrification rates also improve the model performance in reproducing the observed spatial variability of nitrate concentrations in the low-oxygen depths of the AS and BoB. In the BoB, the DeepRem simulation produces nitrate concentrations that compare well with the observations, as the extremely weak denitrification in this sea is well reproduced in the model (Figures 4c and 4d). However, the underestimation of denitrification in the AS in this simulation leads to higher nitrate concentrations there than the observed (Figures 4c and 4d). The reduced nitrate concentration observed in the AS due to denitrification is well reproduced in ShallowRem1 simulation. Yet this simulation also generates a spurious reduction of the modeled nitrate in the BoB due to strongly overestimated denitrification there (Figures 4e and 4f). Finally, as expected, the VaryingRem1 simulation reproduces well the observed nitrate concentrations in the OMZs of both seas (Figures 4g and 4h).

5. Discussion and Conclusions

A set of eddy-resolving model experiments presented in this study highlights the essential role of remineralization depth variations in generating and maintaining the contrasting OMZ intensities of the Arabian Sea (AS) and the Bay of Bengal (BoB), as well as the exclusive presence of denitrification in the AS. These variations in remineralization depth may result from the effect of aggregation of organic matter with mineral particles from rivers in the BoB (Ittekkot et al., 1991). The aggregation is hypothesized to intensify the efficiency of export of organic matter to the bottom waters by increasing the particulate sinking speed or decreasing the remineralization rate by creating an enhanced protection from decomposers (Klaas & Archer, 2002; Le Moigne et al., 2013; Rao et al., 1994).

Here we used low sea surface salinity as a proxy for the riverine input influence. This simplification was possible because low salinity surface waters (<34 psu) in our domain are essentially associated with the river runoff in the BoB (Murty et al., 1992). However, this may not be appropriate in a global or a different regional modeling setup; thus, a better parameterization of the ballasting effect associated with riverine particles would need to be further developed. Additional limitations of the study are inherent to the use of the NPZD biogeochemical model. These include the simplified community structure and the lack of multiple phytoplankton groups as well as the absence of an explicit representation of dissolved organic matter (DOM). Indeed, differences in the community structure or in the semilabile DOM pool between the AS and the BoB can contribute to the observed contrasts in remineralization length scales between the two seas. Additional caveats of the present study include the relatively short duration of simulations that does not allow the quantification of the long-term effects of the varying remineralization depths on the deep (>1,000 m) ocean oxygen. Finally, the mechanisms through which lithogenic particles act on export efficiency are still not clear and require further investigation.

The present model results suggest that estuarine systems such as the BoB most likely transport organic matter more efficiently to the deep ocean than other productive ecosystems (e.g., upwelling systems). They use less oxygen and nitrogen-based oxidant (nitrate and nitrite) for organic remineralization at intermediate depth, thus producing weaker OMZs and limiting or suppressing potential denitrification. However, recent studies suggest that climatic or human-induced factors such as future upper ocean warming in the Indian Ocean (e.g., Lee et al., 2015) may potentially decrease the remineralization depth perhaps by enhancing the remineralization rate (Kwon et al., 2009; Matsumoto, 2007). This may turn systems such as the BoB into an active hot spot of denitrification, with strong implications for the regional and the global nitrogen and carbon cycles, and with ultimately potential feedback on the climate (Bristow et al., 2016). Finally, application of the spatially varying remineralization depth in other regional or global coupled ocean-biogeochemical modeling studies may also improve the model performance in simulating future changes of low-oxygen volumes and denitrification.

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