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Strong Intensification of the Arabian Sea Oxygen Minimum Zone in Response to Arabian Gulf Warming

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Key Points:
- Highly saline, oxygen-saturated Arabian Gulf waters ventilate the Arabian Sea OMZ
- Warming of the Gulf causes reduction of ventilation and expansion of suboxia
- We find nonlinear response of suboxia to warming due to denitrification feedback

Supporting Information:
- Supporting Information S1

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Abstract The highly saline, oxygen-saturated waters of the Arabian Gulf (hereafter the Gulf) sink to intermediate depths (200–300 m) when they enter the Arabian Sea, ventilating the World's thickest oxygen minimum zone (OMZ). Here, we investigate the impacts of a warming of the Gulf consistent with climate change projections on the intensity of this OMZ. Using a series of eddy-resolving model simulations, we show that the warming of the Gulf waters increases their buoyancy and hence limits their contribution to the ventilation of intermediate depths. This leads to an intensification of the OMZ and an increase in denitrification that depletes subsurface nitrate and limits deoxygenation at depth. The projected future concomitant increase of Gulf salinity only partially reduces the OMZ intensification. Our findings highlight the importance of the Arabian marginal seas for the biogeochemistry of the North Indian Ocean and stress the need for improving their representation in global climate models.

Plain Language Summary Dissolved oxygen in the ocean is fundamental for marine life. While relatively abundant in surface waters, oxygen generally declines with depth as it is consumed by organisms' respiration. In certain regions like the Arabian Sea, oxygen concentrations are too low at depth to support marine animals. These are known as “oxygen minimum zones” (OMZs). At their core, extreme oxygen depletion known as suboxia can also cause a loss of bioavailable nitrogen, essential for phytoplankton growth. Using a series of computer simulations, we show that the sinking of oxygen-saturated dense waters formed in the Arabian Gulf contributes to oxygen replenishment of the intermediate depths (200–300 m) in the northern Arabian Sea, reducing the intensity of the OMZ and limiting the volume of its suboxic core. We also show that a warming of the Gulf waters consistent with recent observations and future climate projections limits their ability to sink and ventilate the intermediate depths. This results in a strong intensification of the OMZ and an important loss of bioavailable nitrogen. Our findings highlight the importance of semienclosed seas like the Arabian Gulf for the ventilation of the ocean and hence stress the need for improving their representation in climate models.

1. Introduction

The Arabian Sea hosts the World's thickest oxygen minimum zone (OMZ), with oxygen concentrations being in the suboxic range (<4 mmol/m^3) throughout most of the intermediate ocean (from 150 down to 1,250 m). This widespread suboxia is due to very high rates of biological respiration in the water column combined with a relatively poor intermediate water ventilation. Although it occupies less than 2% of the World Ocean area, the Arabian Sea is responsible for up to 40% of global water column denitrification, a process that depletes the oceanic inventory of bioavailable nitrogen (essential for phytoplankton growth) and releases N_2O (a major greenhouse gas; Bange et al., 2005; Codispoti et al., 2001). The main source of ventilation for intermediate waters in the northern Arabian Sea is the Indian Ocean Central Water—a mixture of aged Antarctic Intermediate Water, Subantarctic Mode Water, and Indonesian Intermediate Water—advected from the south by the Somali current (Olson et al., 1993; Resplandy et al., 2012; You, 1998). Another source of Arabian Sea intermediate water ventilation is the dense and highly saline waters from the Red Sea and the Arabian Gulf, also known as the Persian Gulf (hereinafter referred to as the Gulf; Bower et al., 2000, 2005; Prasad et al., 2001). The denser Red Sea waters ($\sigma_0 \approx 27.2$) sink to depths of 600–1,000 m and mix extensively with other water masses of the Arabian Sea before reaching the OMZ. In contrast, the Gulf waters

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($\sigma_0 \approx 26.4$) remain at shallower depths (150–300 m) and ventilate the upper OMZ more efficiently due to the closer proximity of the Gulf to the Arabian Sea OMZ core (Beal et al., 2000; Morrison et al., 1999; McCreary et al., 2013).

As a semienclosed sea with a very shallow depth (i.e., 35 m on average), the Gulf is particularly vulnerable to amplified warming under climate change. Indeed, recent observations indicate a rate of warming of the Gulf that is 2 to 3 times faster than the average global rate. For instance, Al Rashidi et al. (2009) documented a recent warming of the Bay of Kuwait between 1985 and 2002 at a rate of 0.6 °C per decade on the basis of an analysis of local in situ temperature records. An analysis of sea surface temperature (SST) from the National Oceanic and Atmospheric Administration/National Aeronautics and Space Administration Pathfinder product reveals an average warming of the Gulf of 0.6 °C per decade between 1985 and 2009 (Strong et al., 2011). Furthermore, future climate projections suggest that the Gulf may undergo a substantial warming that exceeds 3 °C and 4 °C by the end of the century under moderate mitigation emission scenario Representative Concentration Pathway (RCP4.5) and business as usual (RCP 8.5) emission scenario, respectively (Hoegh-Guldberg et al., 2014).

Recent observations suggest that the Arabian Sea OMZ may have intensified in the Gulf of Oman over the recent decades. For instance, Ito et al. (2017) show a moderate intensification of the Arabian Sea OMZ over the period from 1960 to 2010. Gomes et al. (2014) documented a dramatic shift in the winter bloom dominant species in the northern Arabian Sea from diatoms to large, green dinoflagellate, Noctiluca Scintillans, which combines photosynthesis from its endosymbiont with ingestion of prey. They linked this change to dropping oxygen concentrations in the region over the same period that give Noctiluca endosymbiont a competitive advantage over diatoms. Another observational study by Piontkovski and Al-Oufi (2015) also documented a recent decline of oxygen and a shoaling of the hypoxic boundary in the Sea of Oman. Finally, using a sea glider survey and historical data, Queste et al. (2018) also suggested a recent intensification of the OMZ in the Gulf of Oman over the last three decades.

The intensification of the Arabian Sea OMZ may not only affect the ecosystem and compress marine habitats but could also lead to enhanced denitrification, thus potentially altering the large-scale marine nitrogen budget and carbon cycle. Yet, the drivers of O_2 decline in this region are still poorly known. In particular, the contribution of the Gulf to the ventilation of the Arabian Sea OMZ remains poorly understood. Here we explore the importance of the Gulf in supplying O_2 to the Arabian Sea OMZ and examine the potential role of the Gulf warming and how it may contribute to these changes. We show that a moderate-to-strong warming of the Gulf, which is consistent with future emission scenarios, can lead to a substantial intensification of the Arabian Sea OMZ and of denitrification. These changes can have important ecological and biogeochemical consequences.

2. Methods

We use version 3.1.1 of the Regional Ocean Modeling System-AGRIF (more details available at http://www.romsagrif.org/). The Regional Ocean Modeling System is a free-surface primitive equations model with orthogonal curvilinear coordinates in the horizontal and stretched terrain following coordinates in the vertical (Shchepetkin & McWilliams, 2005). Advection is formulated using a rotated-split third-order upstream biased operator following Marchesiello et al. (2009). Vertical mixing is represented using the nonlocal K-Profile Parameterization scheme (Large et al., 1994). The biogeochemical model is a nutrient-phytoplankton-zooplankton-detritus model based on nitrogen (Gruber et al., 2006). It includes an oxygen cycle module that is described in detail in Lachkar et al. (2016). At suboxic O_2 concentrations (O_2 < 4 mmol/m^3) nitrification ceases and the remineralization rate is halved. Additionally, aerobic remineralization of detritus is replaced by water column denitrification, where nitrate replaces oxygen as the electron acceptor. Finally, benthic denitrification is represented in the model following the parameterization of Middelburg et al. (1996). More details of the implementation of denitrification in the model are given in Lachkar et al. (2016).

The model domain covers the area extending from 5°S to 30°N in latitude and from 32°E to 78°W in longitude. The model has a horizontal resolution of (1/24)° and a vertical grid made of 32 levels with refined resolution near the surface. The seafloor bathymetry is based on the ETOPO2 data product from the National Geophysical Data Center (Smith & Sandwell, 1997). Smoothing was applied to the topography to minimize pressure gradient errors near steep bathymetry. The model was initialized from rest and forced with

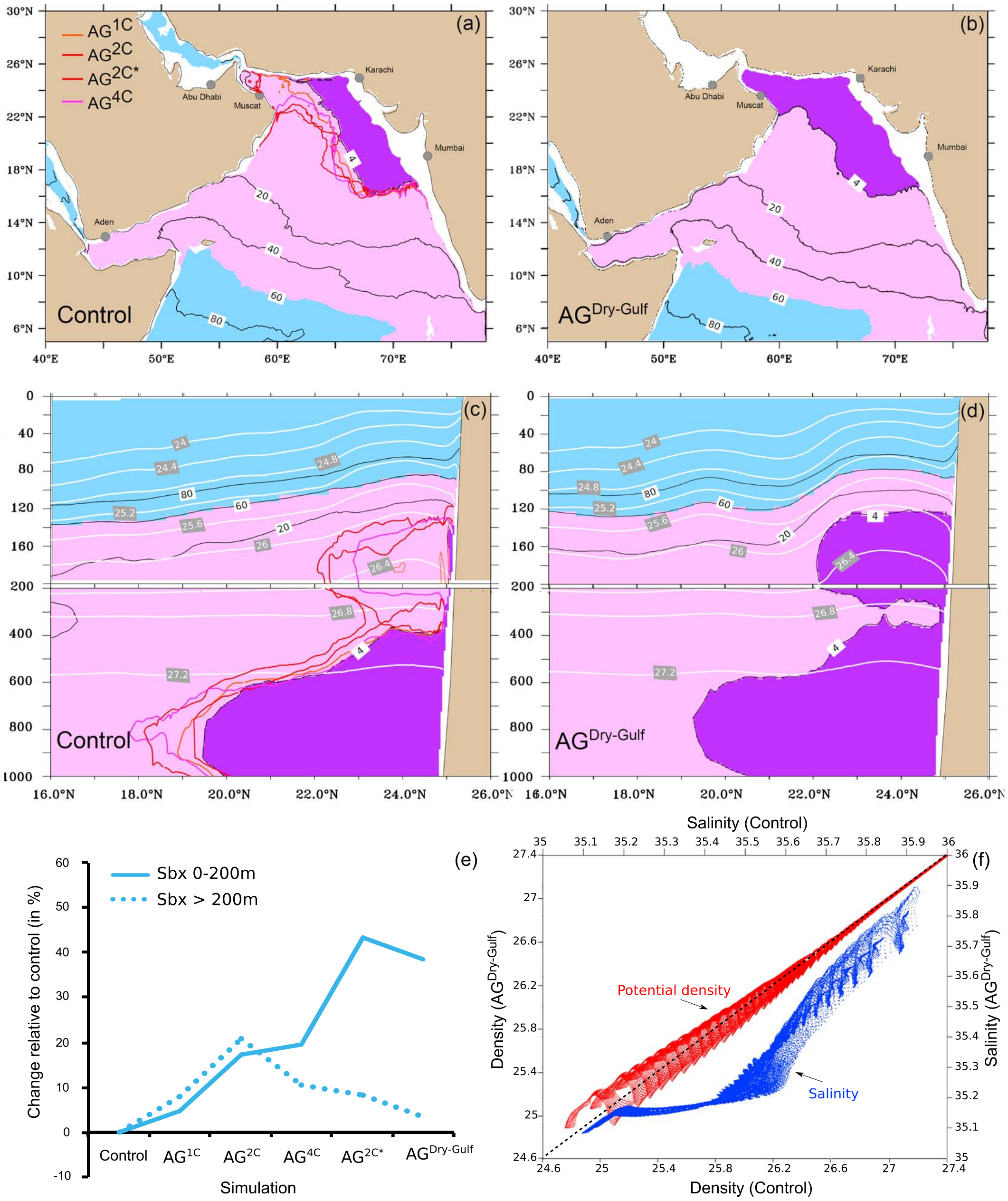

Figure 1. (a–d) Simulated O_2 concentrations (mmol/m^3) in (left) the Control run and (right) the AG$^{\text{Dry-Gulf}}$ run along (top) the isopycnal surface $\sigma_0 = 26.4$ and (bottom) a meridional transect at 60.2°E. The boundaries of the suboxic zone (i.e., $O_2 = 4$ mmol/m^3) simulated under different warming scenarios are superimposed and shown in different colors in (a) and (c). The white contour lines in (c) and (d) correspond to potential density σ_0 surfaces. (e) Relative change (%) of domain-integrated suboxic volume in the top 200 m (solid) and below 200 m (dashed) under different perturbation simulations relative to the control run. (f) Potential density σ_0 (red) and salinity (blue) simulated in the AG$^{\text{Dry-Gulf}}$ plotted against the control run in the layer 100–1,000 m. The dashed black line indicates the identity line.

climatological monthly forcing. Wind stress was derived from the QuikSCAT-derived Scatterometer Climatology of Ocean Winds (Risien & Chelton, 2008). The surface heat and freshwater fluxes are based on the Comprehensive Ocean-Atmosphere Data Set (COADS; da Silva et al., 1994). Surface temperature and salinity were restored to COADS observations using a kinematic heat and freshwater flux corrections following Barnier et al. (1995). The lateral boundary conditions for currents and the initial and boundary conditions for temperature and salinity were derived from the Simple Ocean Data Assimilation ocean reanalysis. The initial and lateral boundary conditions for oxygen and nitrate are based on the World Ocean Atlas 2009.

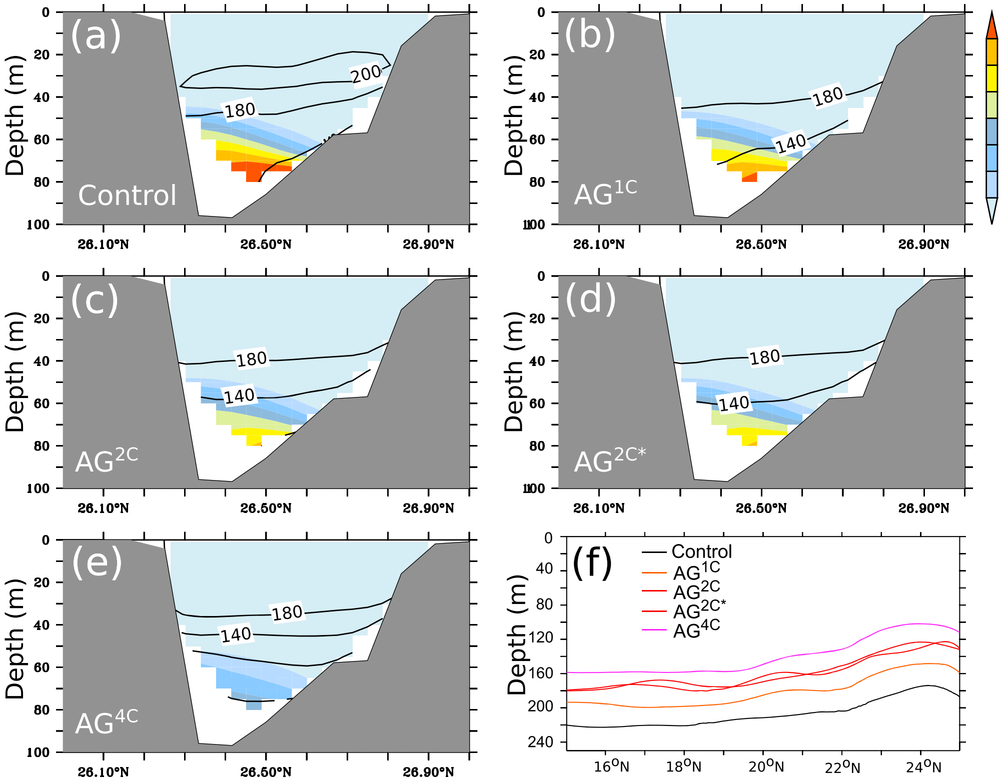

Figure 2. (a–e) Simulated potential density σ_0 across the Strait of Hormuz (56.2°E) in (a) the control run and (b–e) under different warming scenarios. The black contour lines show the corresponding O_2 concentrations (mmol/m^3). (f) Simulated depth of neutrally buoyant Gulf waters (exiting the Strait of Hormuz below 60 m) along 60°E in the control run and under different warming scenarios.

The model is first spun up for 20 years and then is run for an additional 20 years using different perturbation scenarios. In addition to the control run (Control), a first perturbation simulation that consists in closing the Gulf by modifying its bathymetry (AG$^{\text{Dry-Gulf}}$) was performed. The comparison of this first set of simulations aims at evaluating the overall contribution of the Gulf to the ventilation of the Arabian Sea OMZ. In a second set of warming perturbation simulations, the topography was set identical to the control run but the Gulf SST was restored to COADS observations increased by 1 °C (AG^{1C}), 2 °C (AG^{2C}) and 4°C (AG^{4C}), respectively. An additional run was conducted where SST was forced to increase by 2 °C over the Gulf and 1 °C over the rest of the domain (AG^{2C*}). This is aimed at exploring the effect of a weaker concurrent surface temperature increase in the Arabian Sea on the response of the OMZ to the Gulf warming. These runs represent highly idealized scenarios that are not meant to describe realistic future trajectories but rather aim at exploring the sensitivity of the Arabian Sea OMZ to Gulf water temperature changes and improving our understanding of the key mechanisms that control the OMZ response. For model evaluation and oxygen budgets, we generally use the model years 33 to 40. The control run reproduces fairly accurately the observed spatial and temporal variability of the surface circulation and biological productivity and most importantly, the location and intensity of the Arabian Sea OMZ. A detailed evaluation of the control run is provided in Lachkar et al. (2016).

3. Results

3.1. Contribution of the Arabian Gulf to the Ventilation of the Arabian Sea OMZ

Closing the Gulf considerably increases the intensity of the upper OMZ in the northern Arabian Sea (Figure 1). In particular, the layer between $\sigma_0 = 26$ and $\sigma_0 = 26.8$ that is typically ventilated by the Gulf water (Morrison et al., 1999; Prasad et al., 2001) experiences the largest O_2 decrease. This results in a strong intensification of the OMZ in the upper 200 m, with an increase of the volume of suboxic waters by more than 40% in the AG$^{\text{Dry-Gulf}}$ relative to AG$^{\text{Control}}$ simulation (Figure 1). In contrast, the volume of suboxia below 200 m increases by a modest 3% in the dry Gulf case in comparison to the control (Figure 1). These

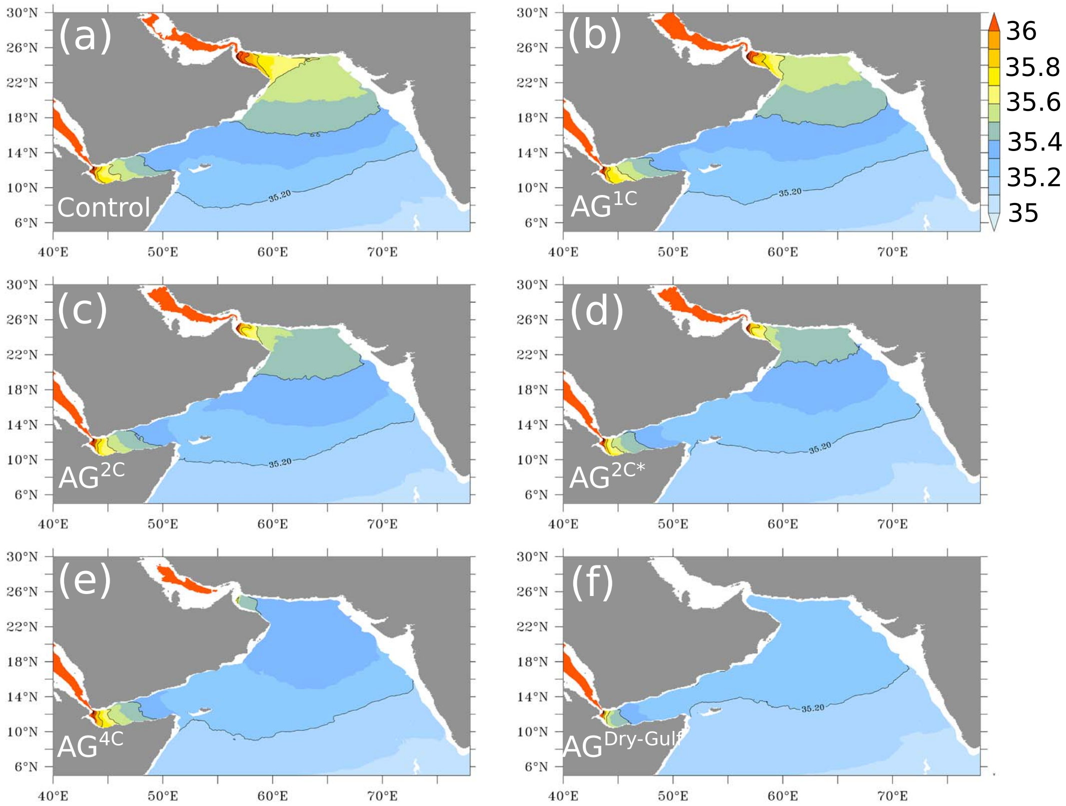

Figure 3. Simulated salinity (psu) in (a) the control run and (b–e) under different warming scenarios along the isopycnal surface $\sigma_0 = 26.4$. (f) Simulated salinity along the same density surface in the closed Gulf run (AG$^{\text{Dry-Gulf}}$).

O_2 changes are associated with no major change in the density structure or circulation between the two simulations (Figure 1 and Figures S1 and S2 in the supporting information [SI]). Yet, important differences in the salinity of water exist between the two runs. Indeed, the closure of the Gulf causes an important decrease of salinity across the upper ocean, a consequence of the halted ventilation of the upper OMZ by the high-salinity Gulf waters (Figure 1). We hence conclude that the Gulf outflow strongly modulates the intensity of the upper OMZ in the northern Arabian. Next, we explore how the warming of the Gulf waters may affect the ventilation of the Arabian Sea OMZ.

3.2. Effects of the Arabian Gulf Warming on the Ventilation of the OMZ

The simulated warming of the Gulf leads to an important expansion of suboxia in the upper OMZ in the northern Arabian Sea (Figure 1). Under strong warming scenarios (i.e., AG^{4C} and AG^{2C*}), the intensification of the OMZ is nearly as strong as in the case of the dry Gulf (Figure 1). For instance, the suboxic volume increases in the upper 200 m by 5% under 1 °C warming and by up to 20% and around 45% in the AG^{4C} and AG^{2C*} warm Gulf runs, respectively (Figure 1e).

In order to better understand the drivers of these changes, we examine the water density across the Strait of Hormuz (56.2°E) that connects the Gulf to the Arabian Sea (Figure 2). We find that the warming of the Gulf waters leads to a decrease in the potential density of the Gulf outflow at the bottom of the Strait of Hormuz (60–80 m) from 26.5 ± 0.1 in the nonperturbed simulation to 25.7 ± 0.1 under the 4 °C warming scenario (Figure 2). Consequently, the more buoyant Gulf outflow waters are not as effective at ventilating the upper (150–250 m) OMZ because they spread at depths which are shallower (100–150 m; Figure 2e and Figure S3 in the SI). The reduction in the ventilation of intermediate layers is also illustrated by the distribution of salinity along the $\sigma_0 = 26.4$ surface depicted in Figure 3. Indeed, the intrusion of the saline Gulf water into the Gulf of Oman decreases as the warming anomaly intensifies. Under the 4 °C Gulf warming (AG^{4C}), the reduction of high salinity in the northern Arabian Sea is nearly as strong as in the case of a dry Gulf.

It is worth noting that the suboxic volume expands more in the AG^{2C*} relative to the AG^{4C} despite a larger reduction of the Gulf outflow in the latter. This is because the warming is applied over the whole model

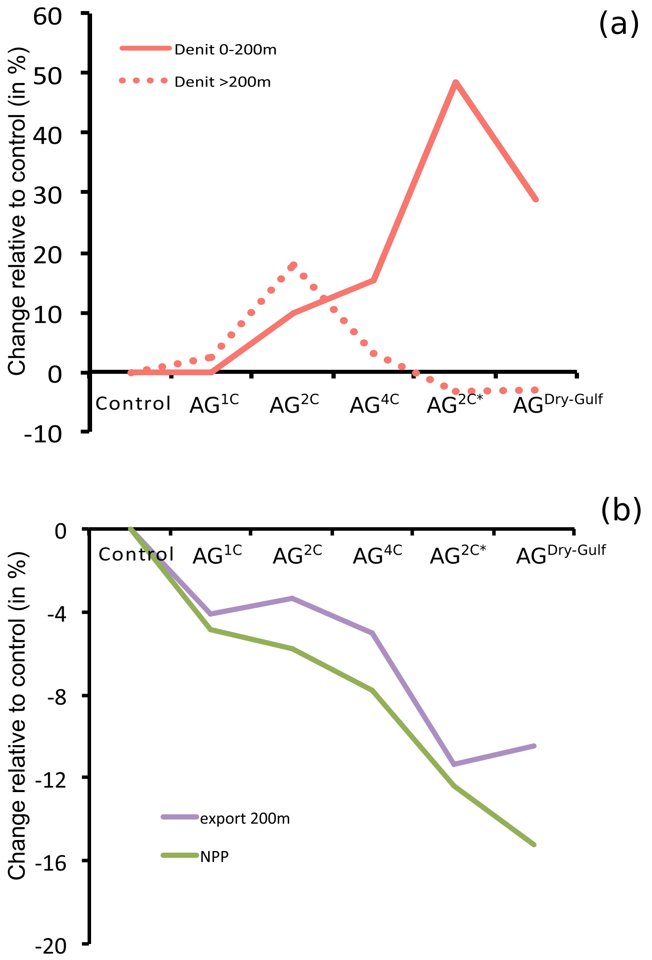

Figure 4. Relative change (%) of (a) domain-integrated denitrification in the top 200 m (solid) and below 200 m (dashed) and (b) net primary production (NPP; green) and export production at 200 m (purple) north of 20°N under different perturbation simulations relative to the control run.

domain in the AG^{2C*} run, causing a domain-wide increase in stratification and decrease in dissolved oxygen in the upper 100 m (Figures S4 and S7 in the SI). This adds up to the effect of reduced ventilation by Gulf waters, leading to a stronger OMZ response. We therefore conclude that the concurrent warming expected over the Arabian Sea is likely to enhance rather than weaken the OMZ response to the warming of the Gulf.

Interestingly, the increase in the suboxic volume becomes weaker under the stronger warming anomalies below 200 m (Figure 1e). In particular, the suboxic volume increases by less than 10% in the AG^{4C} and AG^{2C*} strong warming runs but by around 20% in the AG^{2C} milder warming run. This suggests the existence of a nonlinear response of suboxia to increasing warming beyond which additional warming causes a reduced OMZ response, particularly at depth. In order to understand this nonlinear OMZ response to the Gulf warming, we next consider the effects of denitrification changes on oxygen concentrations at depth.

3.3. Biogeochemical Feedbacks of Reduced OMZ Ventilation

The intensification of the Arabian Sea OMZ results in an important increase in denitrification near the surface. For instance, denitrification is enhanced by 15% and nearly 50% in the upper 200 m in the AG^{4C} and AG^{2C*} strong warming runs (Figure 4a). Below 200 m, denitrification increases by 18% when the Gulf is warmed by 2 °C but only 3% in response to a 4 °C warming perturbation. Denitrification even slightly decreases by around 3% at depth under the AG^{2C*} warming scenario or in the case of a dry Gulf. The enhanced denitrification depletes the subsurface nitrate pool (Figures S5, S6, and S8 in the SI). As nitrification is shut down under suboxic conditions, expanding suboxic volume causes a reduction in nitrification that contributes to nitrate depletion too. However, only enhanced denitrification reduces the total inventory of inorganic nitrogen ($NO_3^- + NH_4^+$) and hence increases nutrient limitation. The depletion of subsurface nitrate causes a reduction of net primary production (NPP) as well as of export fluxes (Figure 4b). This NPP reduction is largest under strong warming scenarios. For instance, under the AG^{2C*} warming scenario, NPP, and export production at 200 m decrease by up to 13% and 11% north of 20°N, respectively. The negative anomalies in NO_3^- concentrations caused by enhanced denitrification are redistributed horizontally, as circulation acts to reduce the amplitude of the nitrate depletion in the northern Arabian Sea through mixing with surrounding NO_3^--richer waters, thus spreading the nitrate reduction beyond the northwest Arabian Sea where denitrification is active (Figures S6 and S8 in the SI). This leads to the reduction in productivity and export fluxes to affect the whole Arabian Sea region. Indeed, the domain (excluding the Gulf) integrated NPP and export fluxes decrease by 4% to 6% in the AG^{2C*} and AG^{4C} runs. A set of additional sensitivity simulations where denitrification was turned off confirms that most of this reduction is driven by enhanced denitrification. Indeed, NPP and export fluxes show a much weaker response to Gulf warming in the absence of denitrification relative to the control (Figure S9 in the SI). This reduction in productivity and export fluxes reduces the biological consumption of oxygen at depth and hence contributes to limit the OMZ intensification below 200 m obtained under strong warming scenarios.

3.4. Role of Salinity Changes

Recent observations suggest an important increase in the surface salinity in several locations of the Gulf (e.g., Al Yamani et al., 2017). For instance, it has been reported that the salinity has increased in the Kuwait Bay over the period 1982–2015 because of a concomitant reduction in Chatt Al Arab discharge in the northern Arabian Gulf (Al Yamani et al., 2017). In general, most future model projections show a salinity increase in the Gulf as a consequence of increased evaporation under climate change (Levang & Schmitt, 2015). For instance, CMIP5 multimodel average indicates an increase in surface salinity by around 0.5 practical salinity unit (psu) under the highest emission scenario (RCP8.5) by 2100 (Levang & Schmitt, 2015). Yet, these projections are associated with important uncertainties caused by (i) the current poor understanding of the future changes in local air moisture especially in wintertime where the Gulf outflow is densest and most effective in ventilating the Arabian Sea intermediate waters and (ii) the strong sensitivity of Gulf salinity to the inflow of Indian Ocean Surface Water, highly vulnerable to monsoon wind changes (Bower et al., 2000; Kämpf & Sadrinasab, 2006).

In order to explore how changes in salinity of the Gulf water may affect the OMZ response to Gulf warming, we performed two additional sensitivity simulations at a slightly coarser resolution of (1/12)° where surface salinity was increased in the Gulf by 0.5 and 1 psu, respectively. These simulations were compared to a new control run performed at an identical resolution (1/12)°. We find that an increase of the Gulf surface salinity by 0.5 psu that is concomitant with a warming of 4 °C, consistent with CMIP5 model projections, still leads to an intensification of the OMZ that is similar to the simulation with no change in salinity. Yet, the denitrification increase is slightly reduced in comparison to the simulation with no change in salinity. Even a stronger Gulf salinity increase by 1 psu is still associated with an important increase of both denitrification and the suboxic volume. Yet, the expansion of suboxia and the intensification of denitrification are nearly 50% weaker relative to the warming scenario assuming no change in surface salinity (Figures S10 and S11 in the SI).

4. Discussion

4.1. Sensitivity to Winter Warming

To further understand the sensitivity of the OMZ ventilation to the warming of the Gulf, we carried out three additional sensitivity simulations that consisted in (1) two simulations where we applied, respectively, a 2 °C and a 4 °C warming to the Gulf throughout the year (similar to simulations AG^{2C} and AG^{4C}) and (2) a simulation where the 2 °C warming was imposed only during winter months (December through February). A comparison of the O_2 and salinity distributions along the isopycnal surface $\sigma_0 = 26.5$ in the three simulations suggests that the warming during winter months is responsible for most of the OMZ intensification (Figures S10 and S11 in the SI). This is consistent with the fact that the Gulf outflow is substantially stronger and denser during wintertime (Bower et al., 2000).

4.2. Sensitivity to Red Sea Warming

Previous studies suggest that the Red Sea (RS) does contribute to the ventilation of the Arabian Sea (Olson et al., 1993). Similarly to the Gulf, the RS is a semienclosed sea that is vulnerable to amplified warming (Chaidez et al., 2017). To explore the sensitivity of the Arabian Sea OMZ to ongoing and future warming of the RS, we carried out two additional simulations where we applied a 2°C and 4°C warming over the RS while keeping the surface temperature elsewhere unchanged. Furthermore, we made a third simulation where the RS was closed. All these three simulations were made at the highest resolution (1/24)° in order to represent the sea floor geometry at the narrow Strait of Bab el Mendeb as realistically as possible. The warming of the RS is shown to reduce the ventilation of the OMZ in the northern Arabian Sea, thus leading to its intensification. But unlike with the Gulf warming, the OMZ intensifies essentially at depth (>400 m) in response to the warming of the RS. In contrast, the response of the upper OMZ (<200 m) is much weaker (Figure S12 in the SI). Additionally, the response of the OMZ scales more linearly with the size of the warming perturbation and only becomes large (>20%) under the 4 °C strong warming scenario (Figure S12 in the SI). The higher sensitivity of the deeper OMZ to the RS warming can be explained by the higher density of the RS water $\sigma_0 = 27$–27.4 that ventilates deeper layers in the northern Arabian Sea (600–1,000 m; Beal et al., 2000; Olson et al., 1993). The more linear response of the OMZ to the RS warming can be linked to the relatively weak changes in the upper ocean suboxia, thus limiting the effect of denitrification feedback on subsurface nitrogen budgets and productivity and hence O_2 consumption at depth (Figure S12 in the SI).

4.3. Implications and Caveats

The Gulf and the RS are separated from the Arabian Sea by narrow and shallow sills ($\approx$ 80 m at the Strait of Hormuz and $\approx$ 130 m at Bab El Mandeb). Therefore, during glacial periods the Arabian Gulf was essentially dry and the Red Sea outflow was strongly reduced (e.g., by 85% during the last glacial maximum) because of the glacial low sea level (Rohling & Zachariasse, 1996; Siddall et al., 2003). Our study suggests that the separation of the Arabian Sea from its two marginal seas may have led to a reduction of the ventilation of the intermediate layers and hence an intensification of the Arabian Sea OMZ during glacial periods. Pichevin et al. (2007) proposed that the cutoff of the two marginal seas outflows during glacial periods may have led to a reorganization of the large-scale circulation in such a way that the ventilation of intermediate layers in the northern Indian Ocean by the Antarctic Intermediate Water from the south is further enhanced. These authors further suggested that this could have led to an increase in the ventilation and a weakening of the Arabian Sea OMZ. Our study does not support this hypothesis as we did not find any noticeable change in the large-scale circulation following the closure of the Gulf (or of the Red Sea). In contrast, our results are consistent with the findings of McCreary et al. (2013) that show an important contribution of the Gulf outflow to the ventilation the OMZ in the Sea of Oman. These authors also found that the ventilation of the OMZ by the Gulf outflow may contribute to the observed eastward shift of the Arabian Sea OMZ (from the region of maximum productivity in the western Arabian Sea).

Our study highlights the importance of the semienclosed seas for open ocean large-scale biogeochemistry. The Arabian Sea marginal seas are typically poorly represented in current generation coarse-resolution climate models as is the Arabian Sea OMZ (Bopp et al., 2013; Cocco et al., 2013). These biases have been linked to several factors including the poor representation of mesoscale eddies and mixing and biases in the representation of biogeochemical processes (Gnanadesikan et al., 2013; Lachkar et al., 2016; Oschlies et al., 2018). Here, we propose that the poor representation of the Arabian marginal seas in these models can also contribute to those biases.

Finally, our study has several caveats and limitations. Among the study's main limitations is the lack of a representation of nitrogen fixation in the model. This could artificially amplify the effect of denitrification on the nitrogen budget and ultimately lead to an overestimated feedback of suboxia on productivity and O_2 consumption. Yet, we believe this effect to likely remain small as denitrification is thought to dominate over N_2 fixation in the Arabian Sea (Bange et al., 2005). Furthermore, although observations suggest a tight coupling between denitrification and N_2 fixation on timescales of thousands of years (Gruber, 2008), the persistent excess phosphate over nitrate in the Arabian Sea indicates a weak coupling between the two processes regionally and on shorter timescales (Gruber and Sarmiento 1997). This is also supported by evidence from paleoclimate records (e.g., Altabet et al., 1999, Altabet et al., 2002). Another major caveat is the use of idealized perturbations that assume that SST changes are uniform either in space or time and hence do not take into account the full complexity of realistic future trajectories. Additionally, the effect of the Gulf warming is taken in isolation of other potential concomitant environmental changes such as changes in large-scale winds (e.g., Lachkar et al., 2018) and circulation or local perturbations such as pollution and eutrophication. Combined, these stressors can lead to antagonistic effects that dampen the overall response or synergistic effects that cause a larger response than that be predicted from individual perturbations considered separately. For instance, recent observations suggest an important decline in the Gulf oxygen content due to pollution and eutrophication (Al Said et al., 2018). This could enhance the effect of warming and lead to stronger OMZ intensification.

5. Summary and Conclusions

A set of high-resolution model simulations reveals a strong vulnerability of the Arabian Sea OMZ to the warming of the Gulf. As they exit the Strait of Hormuz, the warmer Gulf waters gain buoyancy and spread at a shallower depth in the northern Arabian Sea. This results in a decrease of the ventilation of the intermediate (200–300 m) depths, thus causing an expansion of the suboxic volume and an intensification of the upper OMZ. The increase of denitrification that results from the expanded suboxia depletes subsurface nitrate concentrations and leads to a reduced productivity and O_2 consumption at depth. Under moderate warming, this partially compensates the effect of reduced ventilation on oxygen. Under strong warming scenarios, the denitrification feedback can be strong enough to offset the effect of reduced ventilation at depth. The projected future increase in Gulf water salinity can partially mitigate the effect of Gulf warming only to a limited extent as the impact of warming is likely to dominate. Our study suggests that the observed fast warming of the Gulf over the last few decades may have contributed to the recent expansion of the OMZ in the northern Arabian Sea. The projected future strong warming of the Gulf may further enhance this tendency and lead to an increase in the frequency and severity of hypoxic and anoxic events in the northern Arabian Sea together with a strengthening of denitrification, with a potential for a profound alteration of the ecosystems and the biogeochemistry of the Arabian Sea and the Indian Ocean at large.

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