

A revisit to the regulation of oxygen minimum zone in the Bay of Bengal

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Abstract

Occurrence of intense oxygen minimum zone (OMZ) is known in the Bay of Bengal (BoB) but it has been recently reported to have become more acute and is at its tipping point. Here we show that the intensification of OMZ to acute condition is a random and short-term rather than perennial phenomenon based on re-evaluation of old and recent information in the BoB. Short-term modifications in dissolved oxygen (DO) in the OMZ are caused by balance among physical forcings: salinity stratification, occurrence of cyclonic (CE), and anticyclonic eddies (ACE). Our analysis reveals that 'acute OMZ' is only a transient phenomenon in the Bay since the dynamic periodic physical forcings, particularly ACEs, do not allow it to become a dead zone.

Back ground

The open ocean intense oxygen minimum zone (OMZ) is found in the Eastern Tropical Pacific, Arabian Sea and Bay of Bengal (BoB) but the occurrence of denitrification was reported only in the former two basins (eg: Naqviet *al.* 1994). Despite occurrence of conducive conditions for denitrification, its absence in the BoB is attributed to low primary production, rapid sinking of organic matter in association with mineral particles and low bacterial respiration rates (Naqvi *et al.* 1994). Recently Bristow *et al.* (2016) carried out one-time dissolved oxygen (DO) measurement using Switchable trace oxygen sensor (STOX), which is 50 times more accurate than Winkler method, in the northern BoB and found that DO concentrations were much lower than reported and could be at its tipping point in the OMZ. They hypothesized that even a slight increase in primary production due to enhanced nutrients input may lead to the formation of a dead zone in the BoB and trigger anammox. *In situ* observations indicated that eddies modify primary production and DO concentrations in the OMZ in the BoB (eg: Sarma *et al.* 2016). Recent studies using bio-Argos and *in situ* observations revealed that high (low) DO concentrations in the OMZ are associated with ACE (CE) due to convergence (divergence) processes (Sarma and UdayBhaskar 2018; Sarma *et al.* 2018). More recently, Johnson *et al.* (2019) noticed highly variable DO concentrations in the OMZ due to meso-scale eddies, based on 5 years of data from 20 profiling floats equipped with DO and nitrate sensors in the BoB, and suggested that denitrification/anammox is regulated by physical processes that introduce DO. In view of the environmental and climatic significance of intensity of the OMZ in the BoB, we re-visit the issue based on the data collected in the northern BoB during different seasons and years and evaluate 1) whether the intense OMZ is transient or permanent in nature, 2) the potential reasons for occurrence of short-term intense OMZ and 3) the possibility of formation of dead zone in the Bay in near future due to climate change.

2. Data used

We used data collected during 29 November- 12 December, 2013 (Sarma *et al.* 2016), 24 January - 4 February 2014 (Bristow *et al.* 2016), 27 July-19 August, 2014 (Our unpublished data), 25 March-24 April 2016 (WOCE; www.cchdo.ucsd.edu), 23 March - 6 April 2018 (Sarma *et al.* 2018), and 11-29 June 2019 (our unpublished data) and Bio-Argo's data at ACE and outside eddies during 2013-2015 were obtained from Sarma and UdayBhaskar (2018) (Fig. 1). Water column depth, temperature and salinity were measured using CTD (SBE 911 plus, USA) system and the accuracies of these sensors are ± 1 m, $\pm 0.001^\circ\text{C}$ and 0.002 psu, respectively. Dissolved oxygen (DO) was measured using Switchable Trace Oxygen sensor (STOX) during January-February 2014 by Bristow *et al.* (2016) with an accuracy of ± 0.002 μM , whereas DO sensor (SBE 43, USA) was used during other cruises

(March-April 2018, and June 2019) and Winkler titration method was used during August 2010, July-August 2014, and April, 2016. On the other hand, DO was measured using Winkler titration method following potentiometric detection using potentiometer (835 Titrandometrohm, Switzerland) during August 2010, July-August 2014 and April 2016. DO sensors were calibrated using Winkler titration method and appropriate corrections were made. We used Argo-DO data from float No. WMOIDS: 2902086 which measures DO using optode. Though DO sensors (optodes) have some uncertainty in calibration at near zero oxygen levels, they are exceptionally precise and quite stable (Bittiget *et al.* 2018; Johnson *et al.* 2019). The DO sensor gives almost no variations when they are exposed to the anoxic conditions. The accuracy of sensors was determined to be $\pm 0.1 \mu\text{M}$.

Sea level anomaly and derived surface geostrophic currents anomaly used in this study are obtained from Marine Copernicus Environment Monitoring Service (MCEM) Global Ocean reprocessed daily data with a resolution of $0.25^\circ \times 0.25^\circ$. The MCEM combines the data from TOPEX/Poseidon/ERS/Jason-1/Envisat and Jason-2/Envisat. The Monthly sea surface salinity data is taken from Aquarius (OISST V5.0 IPRC gridded product) satellite from Asia-Pacific Data-Research Center (<http://apdrc.soest.hawaii.edu/las8>) with a horizontal resolution of $0.25^\circ \times 0.25^\circ$.

3. Results and Discussion

3.1. Surface characteristics during the study

The BoB is occupied with eddies, both CE and ACE (Chen *et al.* 2012), where ~ 10 eddies form in every 100 km^2 in a year. Since the mixing mechanisms are different between these two types of eddies, the associated chemical characteristics and the surface features of the study region reflect these phenomena. We mapped surface features of sea level anomaly (SLA) and surface currents for the observation periods using satellite data (Fig. 1). The data collected by Bristow *et al.* (2016) was mostly outside the ACE except for the two stations in the south, which are at the peripheral of the ACE (Fig. 1b) while we encountered similar conditions in November-December 2013 (Fig. 1a) with three stations in the ACE. However, all stations were within the ACE during July-August 2014 and March-April 2018 (Fig. 1e) whereas those during March-April 2016 and June 2019 were outside the ACE (Fig. 1f). It is noted that ACEs existed in and around the sampling locations during entire study period and most of the BoB was occupied by high SLA with more ACEs than CEs suggesting the dominance of ACEs (Fig. 1a-f).

3.2. Variability in DO concentrations in the OMZ in the northern BoB

The concentrations of DO found during different sampling periods were plotted in Figure 2. Its lowest concentration ($< 1 \mu\text{M}$) occurred in the depth range 150-450 m (measured using STOX sensor

by Bristow *et al.* 2016) during January - February 2014 when sampling was done at outer boundary of the ACE. The next lower DO concentrations ($\sim 1\mu\text{M}$) were observed during November-December 2013 and June 2019 pertaining to those sampled within or close to CE. However, the concentrations of DO were $3\text{-}6\mu\text{M}$ within ACE during March 2018 (Fig. 2), when it was sampled in the core of ACE, suggesting that nature of an eddy plays a key role in maintaining levels of DO in the OMZ. Johnson *et al.* (2019) measured DO concentrations using Bio-Argo data, in the same region of Bristow *et al.* (2016), and noticed that DO concentrations $<0.5\mu\text{M}$ was found only in the 26% of data and the histogram of data indicate that northwestern BoB is skewed to lower DO concentrations than other parts of BoB. They further suggested that the periods of very low DO ($<0.5\mu\text{M}$) are not the most common conditions.

Shipboard and bio-argo data reveal that DO concentrations were lower (higher) in the OMZ under the CE (ACE) in the BoB and attributed to increase in primary production supported by nutrients inputs to surface through divergence (oxygen input to OMZ through convergence) (Sarma and UdayBhaskar 2017; Sarma *et al.* 2018). Eddies form in the eastern BoB and Andaman Sea and advect towards west or southwestern Bay (Chen *et al.* 2012). DO concentrations in the subsurface waters in the eastern BoB and Andaman Sea are high due to low primary production and high mixing caused by solitons. The advection of ACEs from the east results in oxygen-rich waters transport to the OMZ in the western BoB (Sarma *et al.* 2018). Figure 3 shows vertical distributions of temperature and DO under CE, ACE and no-eddy conditions. Figure 3a suggests that upper 200 m of water column is cooler (warmer) in the CE (ACE) regions compared to that in no-eddy region. DO concentrations at depths below 40 m were lower (higher) in the CE (ACE) region compared to that in no-eddy region (Fig. 3b). Evidently increase in primary production and the consequent sinking carbon fluxes are leading to decrease in DO in the CE region whereas sinking of DO-rich surface waters enhances its levels in ACE region (Sarma *et al.* 2018). Bristow *et al.* (2016) found the lowest concentrations ($<1\mu\text{M}$) of DO during January-February 2014 in the northeastern BoB under the periphery of an ACE. Such low DO concentrations may not have been entirely caused by the weak CE that occurred close to Bristow *et al.* (2016) study region (Fig. 1a) but could have been aided by the inhibition of vertical DO supply by strong vertical salinity stratification.

BoB receives significant amount of freshwater from major rivers, such as Ganges, Brahmaputra and Irrawady, which peaks during June - September period resulting in strong salinity stratification (Sarma *et al.* 2016). The occurrence of lower DO below 100 m depth associated with strong salinity stratification was observed in the northern BoB highlighting that stratification plays a major role on intensifying OMZ than biological processes (Sarma *et al.* 2016). Figure 3c, d depict salinity and DO

profiles in well stratified and weakly stratified regions of the northern BoB during November 2013. Lower DO concentrations between 100 and 200 m in the highly than weakly stratified region suggest that stratification significantly reduces vertical mixing and reduces vertical oxygen supply to the OMZ. Intensification of OMZ in the northern BoB was found associated with strong salinity stratification than in the south (Sarma *et al.* 2016). The satellite sea surface salinity imagery during sampling period (January 2014) suggests that low salinity waters prevailed in the study region (Supplementary Fig. S1) resulting in possible stratification and that could have been the potential reason for the low DO concentrations observed by Bristow *et al.* (2016). Occurrence and spread of low salinity waters is a seasonal feature occurring between August and January with large inter-annual variability (Supplementary Figure S2). Therefore, the impact of salinity stratification on OMZ is a seasonal feature than being permanent.

Therefore, ACEs pump significant amount of surface DO to the OMZ and ventilate the latter. Chen *et al.* (2012) found that annually 10 eddies forms (both CE and ACEs) for every 100 km² in the BoB and further noticed that the size and life time of ACEs are bigger and longer, respectively, than that of CEs in the BoB. At any time, ACEs are present in the BoB (Fig. 1) suggesting the possibility of DO pumping into OMZ in the BoB. Therefore, we strongly believe that measurable amount of DO is always present in the BoB and that low DO concentrations noticed by Bristow *et al.* (2016) cannot be sustained perennially but rather a short-term event caused by salinity stratification (Sarma and UdayBhaskar 2018; Johnson *et al.* 2019). Even then, such low oxygen pockets will be aerated by the ACEs within the next few days to week sat the formation or passage of ACEs in the study region (Fig. 1).

3.3. Feasibility of future intensification of OMZ

DO concentration between 100 and 500 m is close to 1 μ M and sometime it falls to near detection limits. Modifications to water column biogeochemistry and physical processes are expected to alter the intensity of oxygen deficiency. It is hypothesized that BoB may become dead zone in the future either due to human-interference or climate change (Bristow *et al.* 2016). Rapid warming of Indian Ocean (Lee *et al.* 2015) may enhance remineralization of organic matter that may possibly turn the BoB into active denitrification zone. On the other hand, increases in nutrient supply through atmospheric deposition, river runoff, and upwelling are hypothesized to promote primary and export productions and consequently lead to the formation of dead zone in the BoB in the very near future (Bristow *et al.* 2016).

In contrast, sinking carbon fluxes at 100 m were found to be lower in the BoB (< 5% of photic zone primary production), than that in the highly productive Arabian Sea (5-15%), and such low sinking carbon fluxes have been attributed to efficient utilization of organic matter by heterotrophs in the photic zone itself (Anand *et al.* 2018). Sarma *et al.* (2016) noted that >75% of the phytoplankton are picophytoplankton forms due to the prevalence of low inorganic nutrients. Perennial occurrence of oligotrophic conditions is known in the upper 30 to 50 m in the BoB due to strong stratification (Sarma *et al.* 2016), which is expected to intensify due to climate change. Under such inorganic nutrient limiting conditions, picophytoplankton are expected to dominate among other phytoplankton groups. Picophytoplankton are of low density than microplankton and hence the dominant production of the former does not facilitate sinking to deeper depths and thus likely utilized in the upper few 10s of meters. On the other hand, Ittekkot *et al.* (1991) suggested rapid sinking of organic matter along with mineral particles of river origin that lead to less regeneration in the water column and hence weaker OMZ. However, the mineral ballast mechanism is likely mainly in the northern BoB (north of 19°N) where higher river influence and the associated suspended matter is observed (Sarma *et al.* 2016). Dandapat *et al.* (2019 and references therein) found that river discharge from Ganges and Brahmaputra is decreasing in last few decades which might lead to decrease in surface stratification and increase in DO inputs to the OMZ through vertical mixing. This may also increase primary production due to increase in nutrients inputs. The decrease in river discharge also depletes silicate inputs and therefore dominant production may be contributed by smaller phytoplankton leading to less sinking organic fluxes. Rapid warming did not predict in the BoB, unlike Arabian Sea and equatorial Indian Ocean, (Lee *et al.* 2015), therefore increase in remineralization rates and decrease in DO concentrations is unlikely.

Though an increase in atmospheric deposition of inorganic nitrogen may be possible due to climate change (Duce *et al.* 2008), its contribution to open ocean inputs is much smaller as >75% of the land-derived material gets deposited within 10 km from the coast (Yadav *et al.* 2016). Numerical models predicted increase in eddy activity in future due to climate change (eg: Lehahn *et al.* 2011). Such increase may enhance DO ventilation to the OMZ and weaken its acute nature further. Breitburget *et al.* (2018) noticed lack of long-term variations in DO in the OMZ in the BoB that might be due to the balance between DO supply through ACEs and microbial consumption in CEs. Nevertheless, the climate change appears to favor weakening of OMZ than its intensification in the BoB. Despite the presence of anammox bacteria, which reduce inorganic nitrogen to molecular nitrogen, in the BoB (Bristow *et al.* 2016), the BoB appears to more resistant to formation of anoxic zone as DO levels are often well above required for denitrification/anammox to commence. Significant shift in meso-scale

eddies formation and distribution is required in order to occur large-scale denitrification or anammox to occur in the BoB and based on models it seems to be unlikely in the BoB in the future (Johnson *et al.* 2019).

Summary and Conclusions

OMZ in the BoB has been reported to be intensified in the recent years and stated to be at its tipping point. We have revisited to examine mechanisms of maintaining oxygen levels in the OMZ with a focus on whether the tipping point oxygen levels are transient or permanent in the BoB. Our analysis suggested possible OMZ intensification in strong salinity stratification and CE regions due to inhibition of vertical mixing and increase in primary and export production respectively. In contrast, increased DO occurs in ACE regions due to vertical pumping of surface DO into and/or through lateral advection in the OMZ. As more than 10 ACEs form every year for every 100 km² per year in the BoB, intensification and long-term sustenance of DO at tipping point levels in the OMZ is highly unlikely to form in the BoB. The numerical models predicted increase in eddy activity due to climate change, therefore formation of dead zone in the BoB may unlikely even in future. It is suggested that long-term SSH data may be used to examine the variations in size and number of ACEs in the BoB and their impact on OMZ.

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Legend to figures

Figure 1: Spatial variation in Sea Level Anomaly (SLA) in the Bay of Bengal and sampling locations during a) November-December 2013, b) January-February, 2014, c) July-August 2014, d) March-April 2016, e) March-April 2018 and f) June 2019. ACEs and CEs are identified based on sign of SLA and surface circulation.

Figure 2: Vertical distribution of DO (μM) between 100 and 600 m water column depth during a) November-December, 2013 (light blue circles), b) January-February 2014 (red circles), c) July-August 2014 (Blue line with closed circles), d) March-April 2016 (Red line with open circles), e) March-April 2018 (black circles), and f) June 2019 (purple circles). Insert shows the distribution of DO concentrations less than 10 μM .

Figure 3: Vertical distribution of a) temperature and b) DO in the upper 200 m of water column within the CE (black), ACE (blue) and no eddy region (red) from Bio-Argo float (No. WMOIDS: 2902086) and vertical distribution of c) salinity and d) DO in the upper 200 m of water column in the highly stratified (17.8N, 89.4E) and weakly stratified (13.9N, 84.84E) during November-December 2013. Insert shows the variability in DO concentrations between 100 and 200 m depth.

Figure 1:

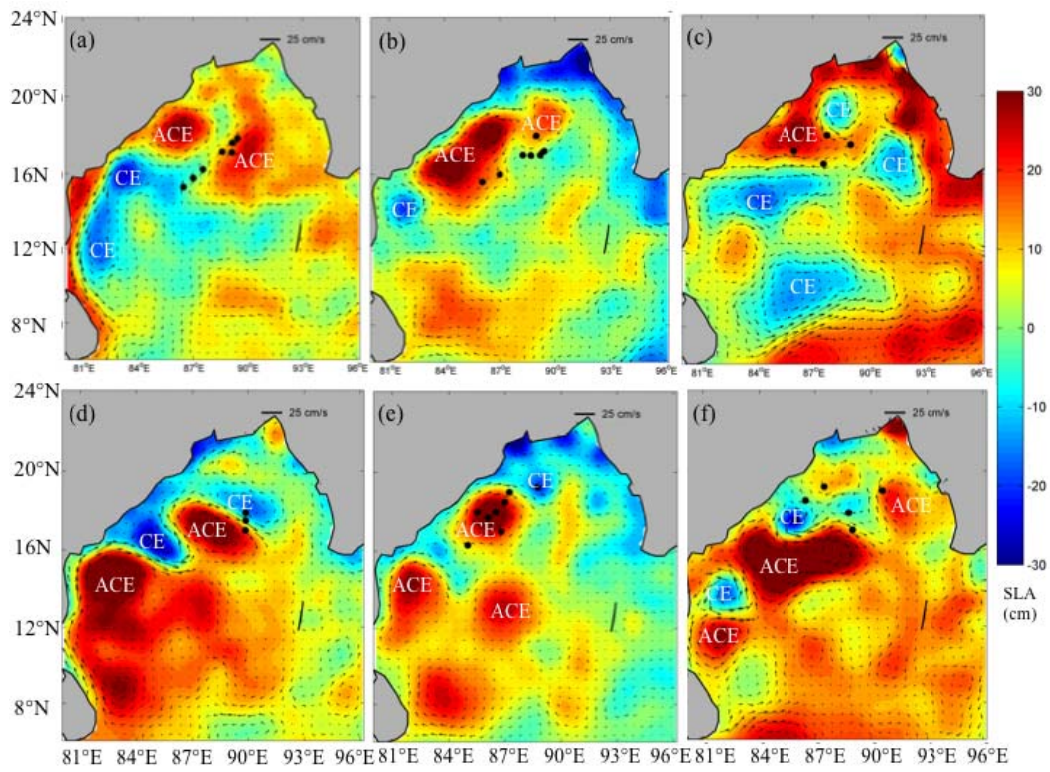


Figure 2:

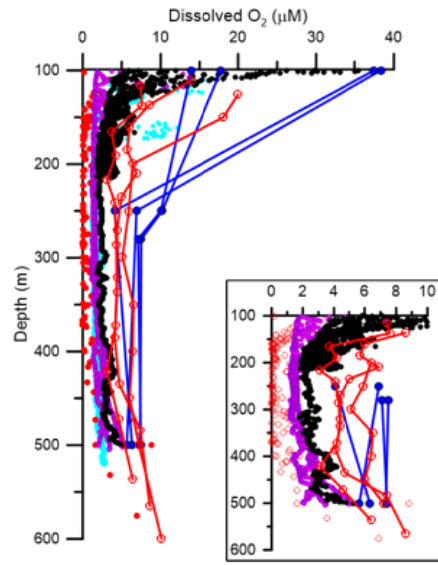
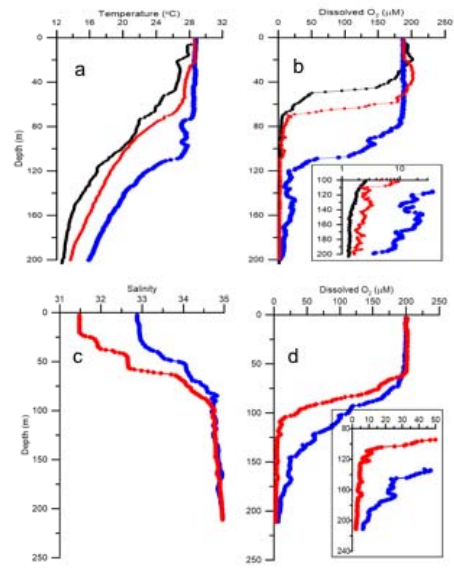
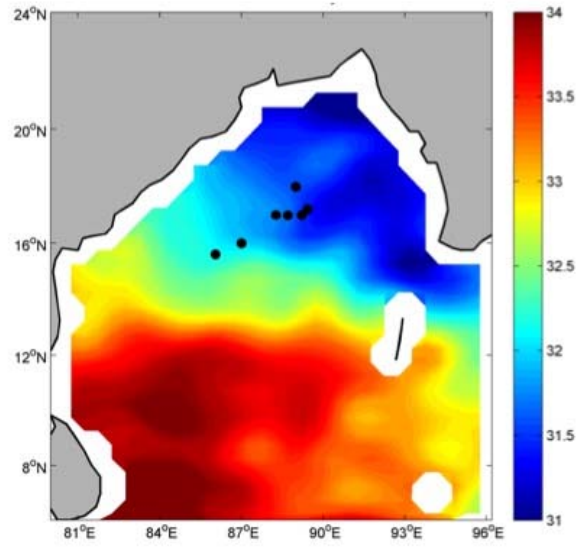


Figure 3:



Supplementary Figure S1:



Supplementary Figure S2:

