

## Ventilation of oxygen to oxygen minimum zone due to anticyclonic eddies in the Bay of Bengal

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### Abstract

Intense oxygen minimum zone (OMZ) occurs in the mid-depth of the Eastern Tropical Pacific (ETP), Arabian Sea (AS), and Bay of Bengal (BoB). However, the occurrence of anammox/denitrification was reported only in the ETP and AS and its absence in the BoB is attributed to presence of traces of dissolved oxygen (DO). Anticyclonic Eddies (ACE) supply high nutrient, organic-rich and oxygen poor waters from the coastal upwelling regions leading to strengthening of OMZ in the offshore of AS and ETP. In the absence of western boundary upwelling we hypothesize that the ACEs supply DO-rich water leading to weakening of OMZ in the BoB. Six ACEs were sampled by bioargo floats and measured *in situ* hydrography and DO. All sampled eddies were formed in the eastern BoB, close to Andaman Sea, and moved towards west. Warm and DO-rich waters were observed in the core of OMZ (150-300m), influenced by ACEs, by 0.5-1.46°C and 3.2-6.5 μM respectively, than no eddy region in the BoB. Based on the mean life time of ACE, the rate of ventilation in the 100-300m was estimated to be 0.07±0.02 μmol/l/d, which is 3 to 4 times higher than bacterial respiration rates (0.02 μmol/l/d). Concerns of OMZ intensification leading to denitrification/anammox conditions in the BoB have been expressed, but with several ACEs forming in time and space in the BoB the denitrification occurrence is unlikely.

Key words: Anticyclonic eddy, dissolved oxygen, oxygen minimum zone, ventilation, Bay of Bengal.

## 1. Introduction

Oxygen minimum zones (OMZ) account for about 20–40% of oceanic nitrogen loss to the atmosphere through heterotrophic denitrification and anammox [Devol, 2003; Arrigo, 2005; Kuypers *et al.*, 2005]. In the global ocean, the existence of strong OMZ is reported in the Eastern Tropical Pacific (ETP), Arabian Sea (AS) and Bay of Bengal (BoB). However, denitrification and/or anammox are confined to the former two basins [eg: Naqvi *et al.*, 1991; Gonzalez *et al.*, 2014; Ward *et al.*, 2009; Pitcher *et al.*, 2011; Rush *et al.*, 2012; Kalvelage *et al.*, 2013]. Although the conditions appear to be conducive for denitrification/anammox to occur in the BoB, its absence is attributed to incomplete oxidation of organic matter due to mineral ballast leading to relatively higher oxygen in the OMZ of the BoB than in the AS and ETP [Ittekkot *et al.*, 1991; Rao *et al.*, 1994; Naqvi *et al.*, 1994; Sarma *et al.*, 2016]. Advection of organic detritus from the upwelling region to the OMZ is suggested to be one of the important factors to intensify OMZ in the ETP and AS, however, such sources are weak in the BoB due to strong stratification [McCreary *et al.*, 2013]. In addition to this, low surface primary production, due to strong near-surface stratification leading to reduction of nutrient entrainment into the euphotic zone, is another reason for OMZ to remain weak in the BoB [Sarma, 2002a,b; Prasanna Kumar *et al.*, 2004; Narvekar and Prasanna Kumar, 2007].

Recently Bristow *et al.* [2017] noticed very low levels of oxygen in the BoB, which they called as the tipping point concentration, and its further decrease even by a trickle would herald anammox conditions. The authors hypothesized that increase in atmospheric deposition of nutrients and changing intensity of summer monsoon in the future might enhance primary production that would in turn increase organic matter decomposition and oxygen consumption leading to occurrence of anammox. However, the occurrence of intense OMZ depends on the balance between oxygen inputs and its consumption, but not alone by biological production [Sarma, 2002a,b].

Horizontal advection of highly oxygenated intermediate water, which is formed along the northern edge of the Antarctic Circumpolar Current (ACC), is a major source of oxygen to OMZ in the northern Indian Ocean [McCreary *et al.*, 2013]. Competing with this mechanism is vertical diffusion of oxygen through thermocline, which is more important than horizontal supply, to maintain OMZ [Sarma, 2002a,b]. In support of this, Sarma *et al.* [2016] recently noticed deepening of the upper boundary of OMZ under the anticyclonic eddy (ACE) and suggested that eddies may ventilate DO to the OMZ. As indicated by *in situ* data, ACEs can extend to sub-thermocline and even greater depths [up to 900 m; e.g., Bower *et al.*, 2005; Davis, 2005]. ACEs are also strong source of nutrients to the open ocean region in the ETP and AS as they transport nutrient-rich upwelled suboxic waters

from the coastal region to the oligotrophic open ocean region, and such eddies may intensify OMZ [D'ottone *et al.*, 2016]. In contrast, the eastern BoB, where eddies are formed, is relatively more oxygenated in the water column (above 1000m) and no upwelling occurs due to strong salinity stratification[Sarma and Narvekar, 2001; Chen *et al.*, 2012]. Hence, ACEs in the BoB is expected to bring oxygen rich and nutrients poor waters to the open ocean.

Chen *et al.*[2012] reported that as many as ~10 eddies form in the northernBoB per 1° grid, and that their frequency decreases towards south (south of 5° N) due to weakening of Coriolis force that is required to maintain their dynamic balance. Significant work was carried out on role of cyclonic eddies on primary production and nutrient inputs in the BoB[Prasanna Kumar *et al.*, 2004; Narvekar and Prasanna Kumar,2007; Vidya and Prasanna Kumar, 2013], however, the biogeochemical characteristics of ACE and their impact on OMZ are unknown in the northern Indian Ocean. The objective of the present study is to test the hypothesis that ACE supplies significant amount of oxygen to the OMZ that would prevent it from becoming anoxic or a dead zone in the BoB.

## 2. Material and methods

We used *in situ* data from a bio-Argo float (WMOIDs 2902086) for this analysis. The bio-argo float is a platform fitted with standard Seabird SBE-41CP CTD sensor for measuring pressure, temperature, salinity and dissolved oxygen (DO) (Aanderaa Optode 4330 sensor). The accuracies of these sensors are 2.4 db, 0.002°C, 0.005 psu, and <8 µM respectively. The float measures data at predetermined depth intervals corresponding to every meter between surface to 10m, every 5m in the depth range of 10 to 200m and every 10m between 200 and 500m and every 20-25 m from 500 to 2000 m during ascent. The temperature and salinity data were quality controlled following Wong *et al.* [2015] and UdayaBhaskar *et al.*[2012] whereas DO data usingThierry and Bittig[2016]. All the profiles were visually checked for the occurrence of unusual spikes and other spurious values. In addition to this, Argo's DO profiles were calibrated with *in situ* measured DO data collected during cruises in the BoB(R/V SindhuSadhana, July-August 2014; SSD#001; Fig. 1) and difference (<6 µM) is within the accuracy of the sensor.The Bio-Argo's data can be obtained from <http://www.coriolis.eu.org/Data-Products/Data-Delivery/Argo-floats-by-WMO-number>.

The bio-argo float (WMOIDs 2902086) sampled the upper 2000 m of water column at 5 days interval. This float was deployed on 29 December 2012 at 12.11°N, 88.72°E and taken 244 profiles until 10 February 2016 (18.19°N, 84.61°E). While bio-argowas functional between 2012 and 2016, severalACEs passed through the sampling location, of which the profiler covered 6ACEs with 4 to 6 profiles in each ACE(Fig. 2). In order to show the variability in water column properties, the data

collected within ACE and outside eddy region were plotted for comparison at each instance. The details of transect (beginning and end position), positions of eddy sampling region, the difference in DO at 100 m (boundary of the OMZ), and mean between 150 and 300 m (the core of the OMZ), difference in temperature between 150 and 300m and sea surface height anomaly (SSHA) at the core of the eddy sampled are given in Table 1.

The daily SSHA data was obtained from Ssalto/Duacs altimeter products that are produced and distributed by the Copernicus Marine and Environment Monitoring Service (CMEMS) (<http://www.marine.copernicus.eu>) at 25km spatial resolution. The details of acquisition, quality control and gridding are given in Pujol *et al.* [2016]. The surface geostrophic currents data were computed from altimetry following Stewart [2008]. 3-D plots were drawn using Ocean Data View (ODV), and 2-D plots using Grapher software. Statistical analysis was carried out using Statistica.

### 3. Results and Discussion

#### 3.1. Influence of anticyclonic eddies (ACEs) on vertical distribution of oxygen

During the bio-argo's life time (2012-2016), it sampled 6 ACEs in the central BoB. The SSHA at the core of the sampled ACEs varied between 7.5 and 28cm and anticyclonic geostrophic currents were observed within the sampled ACEs (Fig. 2). The cross-sectional area of each ACE varied between 35 and 220 km, which are consistent with the mean value of 137 km in the BoB [Chen *et al.*, 2012]. The temperature, and DO in the upper 300m of water column were significantly higher within the ACE compared to the outside eddy region (Fig. 3) suggesting that ACEs are strong source of DO to the OMZ. Figure 4 shows variations in water column characteristics within and outside ACEs. Deepening of isolines of temperature, salinity and DO were observed within the ACEs compared to outside eddy region. For instance, the depth of oxycline (assumed as 15 $\mu$ M of oxygen isoline) deepened from 160m depth in the outside eddy region to >300 m within the ACE in Eddy 1 (12 April to 7<sup>th</sup> May 2013; Fig. 2). Similarly deepening of oxycline was observed from 110 to 220 m in Eddy 2 (9 September to 10 August 2013) and 200 to 250 m in Eddy 3 (24 October to 13 November 2013) (Fig 3). The mean concentration of oxygen within the ACE region was higher by 24-87  $\mu$ M at the 100 m depth whereas 3.2 to 6.5  $\mu$ M between 150 and 300 m depth range relative to outside eddy region (Table 1) suggesting that ACEs enhanced significant amounts of DO to the OMZ.

Gordon *et al.* [2017] noticed intra-thermocline eddy at subsurface depths with the water characteristics of Andaman Sea in the western BoB and suggested that eastern BoB and Andaman Sea provides the source waters for eddies in the BoB. All 6 sampled ACEs were originated in the

eastern BoB (Fig. 2) and advected to the west. In order to compare water column characteristics, vertical profiles of DO were compared in the no-eddy regions in the east and western BoB using the *in situ* data collected during July-August 2014 [SSD #001; Fig. 5]. Relatively higher DO concentrations were observed between depth range of 250 and 1000 m of water column in the eastern Bay ( $22.6 \pm 5 \mu\text{M}$ ; blue curve in Fig. 5) compared to western BoB ( $15.0 \pm 3 \mu\text{M}$ ; red curve in Fig. 5) and it was attributed to low primary production due to high suspended load driven by river discharge [Sarupria and Bhargava, 1998; Sarma and Narvekar, 2001; Unger *et al.*, 2003; Suwannathatsa and Wongwises, 2013]. Therefore advection of eddy towards west (Fig. 2) brings DO rich waters to the central and western Bay.

The concentrations of DO in the OMZ are modified by several pathways - (a) ACEs significantly increase oxygen in the OMZ through deepening of mixed layer in the open BoB [Sarma *et al.*, 2016], (b) river driven stratification in the coastal BoB results in decrease in oxygen in the OMZ [Sarma *et al.*, 2013b; 2016] and (c) lateral supply from the eastern to western BoB in the upper 1000m of water column through ACE enhances DO in the OMZ. The depth of 20°C isotherm (D20) deepened by 20-50 m in the ACE compared to no-eddy region associated with deepening of oxycline suggesting that significant supply of oxygen from the mixed layer to OMZ in the ACE region (Fig. 4). All sampled ACEs were warmer ( $0.5$  to  $1.46^\circ\text{C}$ ) and enriched oxygen ( $3.3$ - $6.5 \mu\text{M}$ ) in the subsurface waters (150-300 m) than no eddy regions suggesting that the waters within the ACE were significantly ventilated DO via the horizontal advection from the eastern BoB (Fig. 2; Table 1). The depths of warming and oxygenation in the sampled ACEs showed significant variability with reference to SSHA. For instance, relatively higher amount of DO was noticed to the greater depth in Eddy 2 followed by Eddy 1 and Eddy 3 and it is associated with high SSHA in the former than latter eddies suggesting that intense mixing may be possible during former than latter eddies (Table 1; Fig. 4). Gopalan *et al.* [2000] found that eddies do not extend to the surface due to strong salinity stratification as to why SSHA is suggested as a better proxy than sea surface temperature to identify eddies in the BoB. Therefore, SSHA is a good indicator of zones of oxygen injection to the OMZ.

Prakash *et al.* [2013] observed significant linear correlation between oxycline and thermocline suggesting that physical processes played significant role on the variations in oxycline depth than biology. Sarma *et al.* [2016] also observed linear correlation between the depths of 20°C isotherm and 20  $\mu\text{M}$  DO isoline in the BoB using *in situ* observations during post-monsoon period. In contrast, biology plays a dominant role in determining the absolute concentration of DO in the OMZ or defining the strength/intensity of the OMZ, whereas vertical movement of the thermocline governs

the boundary of OMZ. This is consistent with *Girishkumar et al.*[2011] who suggested that large scale planetary waves, viz., Rossby waves and coastal Kelvin waves, cause oscillations in the thermocline and hence the oxycline depth [*Prakash et al.*, 2012; 2013]. Similarly co-variability of thermocline and oxycline was also reported off Peru in the equatorial Pacific [*Morales et al.*, 1999; *Thomsen et al.*, 2016]. *Zhong et al.*[2016] gave observational evidence for strong ageostrophic motions in an ACE extending to the upper 300 m of the water column in the northern South China Sea. In case of the BoB, ACEs brought oxygen rich waters from the eastern BoB into the intense OMZ waters of central BoB, than vertical mixing due to strong stratification, thereby resulting in weakening of the strength of OMZ in the central BoB and this feature is well captured by the bio-argo floats.

### 3.2. Impact of ACE on denitrification/anammox in the OMZ

The vertical distribution of DO suggests that 2-4 $\mu$ M of DO present in the depth below 200m in the no eddy region [Fig. 2; *Sarma et al.*, 2016] and lower concentration of <0.2  $\mu$ M was observed using switchable trace oxygen sensor at the depth below 150m in the BoB [*Bristow et al.*, 2017]. *Bristow et al.*[2017] observed anammox bacteria within the OMZ waters, peaking at the 150m depth, however, absence of nitrogen formation and nitrite presence was attributed to persistent DO concentrations up to 0.2  $\mu$ M. Increased DO concentrations above 4-5  $\mu$ M at this depth should lead to inhibition of anammox. Our study suggests that ACEs bring significant amount of oxygen to the OMZ leading to inhibition of anammox/denitrification in the BoB. In contrast, advection of organic matter rich and DO-poor waters from the western boundary upwelling region by ACEs leading to strengthening of OMZ and occurrence of denitrification and anammox in the eastern Tropical Pacific (ETP) [*Devol*, 2003; *Arrigo*, 2005; *Gonzalez et al.*, 2014] and eastern equatorial Atlantic Ocean [*Lukas and Santiago-Mandujano*, 2001; *Stramma et al.*, 2014; *Karstensen et al.*, 2015]. This is consistent with *McCreary et al.*[2013] who suggested that supply of detrital organic matter from the upwelling region intensifies OMZ in the Arabian Sea while the lack of strong western-boundary upwelling may be the potential reason for its absence in the BoB.

The occurrence of denitrification/anammox is controlled by the balance between supply and demand of DO in the OMZ. *Chen et al.*[2012] studied radius (size), life span, seasonality and number of eddies in the BoB using satellite altimetry data between 1992 and 2009. They identified 4,701 and

4,713 anticyclonic and cyclonic eddies in 532 and 525 tracks respectively between 1992 and 2009. The mean ACE size was 134 km with life span of 8.9 weeks (62 days) in the BoB. Based on this data, the rate of oxygen input to the OMZ was estimated to be 0.052 to 0.102 (mean  $0.07\pm 0.02$ )  $\mu\text{mol/l/d}$  using mean difference of DO between 150 and 300 m, within and outside ACE, as 3.2 to 6.5  $\mu\text{M}$  (Table 1), and mean eddy life span of 62 days. *Naqvi et al.* [1996] measured bacterial respiration rates in the BoB to be  $0.02\pm 0.004$   $\mu\text{mol/l/d}$  during winter. Though seasonal variability of bacterial respiration rates is unknown, however, our present study suggests that the supply of DO through ACE is 3 to 4 times higher than bacterial consumption (respiration rates) in the OMZ suggesting that ACEs supply significant amount of DO to OMZ to prevent formation of anoxic conditions and denitrification/anammox in the BoB. Though these estimates carry significant amount of errors due to lack of information on bacterial respirations rates within the ACEs, mixing of water masses with variable characteristics within the ACEs and mixing rates in the ACEs, however, these estimates give first-hand information on importance of ACEs on oxygenation of OMZ. The bacterial respiration rates in the OMZ should be measured in future to evaluate the role of eddy driven oxygen supply in suppressing nitrate reduction in the OMZ.

In addition to the ventilation of DO through vertical mixing, horizontal advection of DO is also important [*Sarma, 2002a,b; McCreary et al., 2013*]. The major source of oxygen to the OMZ is from the Southern Hemisphere, which brings highly oxygenated, intermediate water, formed along the northern edge of the Antarctic Circumpolar Current (ACC). Recently, *Jain et al.* [2017] noticed occurrence of DO rich and high salinity Persian Gulf Watermass (PGW) in the depth range of 250-400m in the BoB, which is the core of OMZ. The increase in DO due to PGW was found to be 13.4 to 22.3  $\mu\text{M}$  in the OMZ [*Jain et al., 2017*]. Considering the mean ventilation time of OMZ to be 12 years [*Sarma, 2002b*], the rate of oxygen input through PGW is estimated to be 0.003 to 0.005  $\mu\text{mol/l/d}$ . *Queste et al.* [2018] suggested that PGW may not bring significant amount of DO to the BoB as it passes through intensely DO depleted OMZ of the Arabian Sea before entering to BoB. Nevertheless, the supply of oxygen through horizontal advection of PGW is an order of magnitude less than that from ACEs ( $0.07\pm 0.02$   $\mu\text{mol/l/d}$ ) and bacterial respiration rates ( $0.02\pm 0.004$   $\mu\text{mol/l/d}$ ), suggesting that ventilation of oxygen through ACEs is very important in the maintenance of OMZ. *Sarma* [2002] suggested that supply of oxygen at the upper boundary of OMZ is relatively more important than horizontal advection to maintain the OMZ in the BoB. In contrast, this study suggests that horizontal advection of oxygen through ACE may play equal role in controlling oxygen concentrations in the OMZ in the BoB. Therefore, this study suggests that DO ventilated to the OMZ

through ACEs (both vertically and horizontally), and by horizontal advection through PGW, to a lesser extent, is much more than is needed to intensify OMZ to a threshold that denitrification/anammox can occur. Though ACEs are important source of DO to the OMZ, however, the supply of DO through them is not a constant phenomenon. It is depended on the formation rate (number of eddies formed), area of their coverage, age, mixing conditions within the eddy, and regions of formation are highly important to the magnitude of DO injection and intensity of OMZ. Many of the biogeochemical models used in the northern Indian Ocean do not include meso-scale features [McCreary *et al.*, 2013], and ask for their attention at high spatial and temporal resolution so that the maintenance of OMZ is understood better.

#### **4. Summary and conclusions**

Intense OMZ occurs in the mid-depths of eastern tropical Pacific (ETP), Arabian Sea (AS) and Bay of Bengal (BoB), however, the occurrence of denitrification/anammox was reported only in the former two basins due to presence of significant amount of oxygen in the latter basin. We hypothesized that anticyclonic eddies (ACE) ventilate dissolved oxygen (DO), both vertically and horizontally, leading to weakening of OMZ in the BoB. Six ACEs were sampled for DO between 2012 and 2016 by bio-argo float within and outside ACE in the BoB. As hypothesized, ACE ventilated warm and DO rich waters to the OMZ leading to increase in DO by 3.2 to 6.5  $\mu\text{M}$  in the depth range of 150-300 m. Based on the mean life time of ACE, the rate of ventilation was estimated to be  $0.07 \pm 0.02 \mu\text{mol/l/d}$ , which is 3-4 times higher than bacterial respiration rates ( $0.02 \mu\text{mol/l/d}$ ). Though supply of DO through ACEs is not constant as it depends on number of eddies formed, size, life time, and formation region that controls intensity of OMZ and its maintenance.

*Bristow et al.* [2017] attributed that DO in the BoB is at a tipping point and small variations in processes, such as input of nutrients from rivers, atmosphere, and upwelling, may increase primary production in future leading to formation of dead zone in the BoB. Based on the numerical models, *Matear and Hirst* [2003] found that DO in the subsurface waters of global ocean may be decreased in the future due to variations in the circulation pattern, however, they further mentioned that it is rather compensated by decrease in export production and respiration rates. On the other hand, increase in river runoff from Ganges and Meghna rivers (not much changes in Brahmaputra) are projected in the next century [Mirza *et al.*, 2003; Masood *et al.*, 2015] resulting in increased terrestrial mineral particles to the BoB. This would lead to ballast of organic matter to the depth with limited oxidation in the water column [Ittekkot *et al.*, 1991]. Under enhanced river discharge scenario in future, coastal upwelling may be weakened due to increased stratification caused by river discharge [Mirza *et al.*,



2003; *Sarma et al.*, 2015; *Masood et al.*, 2015]. Even under increase in river discharge scenario, nutrients may not be added to BoB as river-borne nutrients are consumed within the few kilometres from the coast [*Sarma et al.*, 2013b; *Krishna et al.*, 2015]. More importantly, enhanced eddy activity is predicted in future and its impact is unknown on biogeochemistry of the ocean [*Meredith and Hogg*, 2006, *Fyfe et al.*, 2007; *Lehahn et al.*, 2011]. All these predictions suggest that possible formation of anoxic zone and occurrence of anammox/denitrification in future may be unlikely in the BoB. Therefore, long-term monitoring of changes in DO concentrations using bio-argo floats should be carried out in the north Indian Ocean in order to examine the modifications in these sensitive regions in future.

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Table 1: Position of transect and eddy sampling regions, change in temperature and DO between ACE and no eddy region at 100m and 150-300 m in the BoB

Eddy Number	Start date of transect	End date of transect	Start-End Position of Transect (°N)	Start-End Position of Transect (°E)	Start-End position of eddy sampling (°N)	Start-End position of eddy sampling (°E)	Diameter of the eddy (km)	Maximum SSHA in the ACE (cm)	Difference in temperature between eddy and non-eddy between 100 and 300m (°C)	Difference in DO between eddy and non-eddy region at 100m (µM)	Difference in mean DO between eddy and non-eddy between 150 & 300 m (µM)
Eddy 1	11 Feb 2013	27 May 2013	12.10 12.06	87.84 87.73	11.28 11.95	86.76 87.02	220	19	1.30±0.3	35±5	6.5±2
Eddy 2	7 May 2013	09 Sep 2013	11.95 11.93	87.02 88.89	12.67 11.93	86.76 88.89	113	28	1.46±0.2	87±12	3.5±1
Eddy 3	24 Oct 2013	08 Dec 2013	12.87 12.70	86.77 86.76	12.87 12.87	86.77 86.95	35	17	1.23±0.4	32±6	3.2±1
Eddy 4	28 Dec 2013	08 Mar 2014	13.02 13.76	86.52 86.40	13.87 13.89	85.76 86.09	166	17	1.89±0.3	29±4	4.5±1
Eddy 5	26 Jul 2014	08 Dec 2014	13.59 13.37	86.15 86.08	13.74 13.21	86.21 86.44	84	07	0.51±0.2	24±5	3.3±2
Eddy 6	29 Oct 2015	07 Jan 2016	14.44 15.31	86.56 83.61	15.52 14.41	83.74 84.28	110	15	1.15±0.3	30±6	4.2±2

## Legend to figures

**Figure 1:** Comparison of dissolved oxygen measured by optode sensor fitted on the Bio-argo float with Winkler titration method during July-August 2014.

**Figure 2:** Sea surface height anomalies (cm; color scale) and Bioargo float transect during different periods a) February-May 2013, b) May-September 2013, c) October-December 2013, d) January-May 2014, e) July-December 2014, and f) October 2015 -January 2016. The left panel shows with reference to longitude and right panel with reference latitude.

**Figure 3:** Vertical distribution of temperature ( $^{\circ}\text{C}$ ) and DO ( $\mu\text{M}$ ) within ( $12.85^{\circ}\text{N}$ ,  $86.95^{\circ}\text{E}$  on 8 November 2013) and outside the ACE ( $12.58^{\circ}\text{N}$ ,  $86.89^{\circ}\text{E}$  on 23 November 2013) in the BoB.

**Figure 4:** Variations in water column temperature (left panel), salinity (middle panel) and dissolved oxygen ( $\mu\text{M}$ ) (right panel) during different periods between 2013 and 2016 in the BoB. The left side figures show the Bioargo positions where data were collected. The red coloured positions where ACE was sampled and black colour positions denote no eddy region. The red line on the contour plots denotes ACE region. Identify the starting position of the transect, i.e. zero on x- axis, in blue color circle. Sampling dates of ACE was also given (date and month) next to red circles.

**Figure 5:** Comparison of vertical profiles of DO in the eastern ( $14.75\text{N}$ ,  $90.64\text{E}$ ; Blue) and western BoB ( $17.2\text{N}$ ,  $86.00\text{E}$ ; Red) during June 2015.



**Figure 1:**

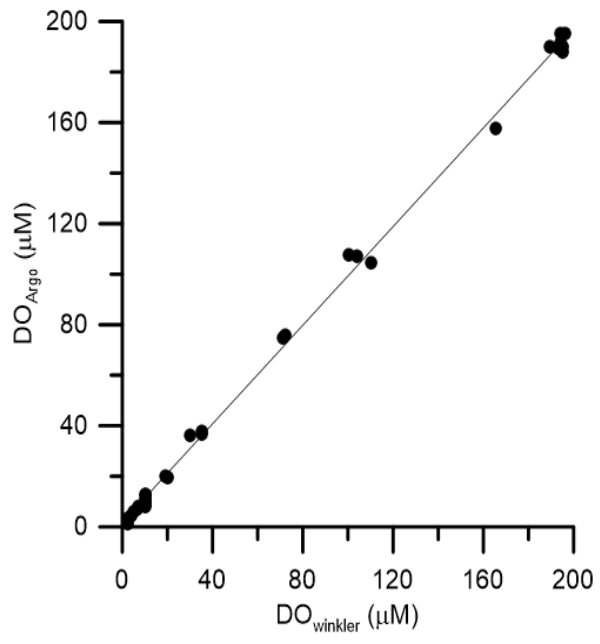
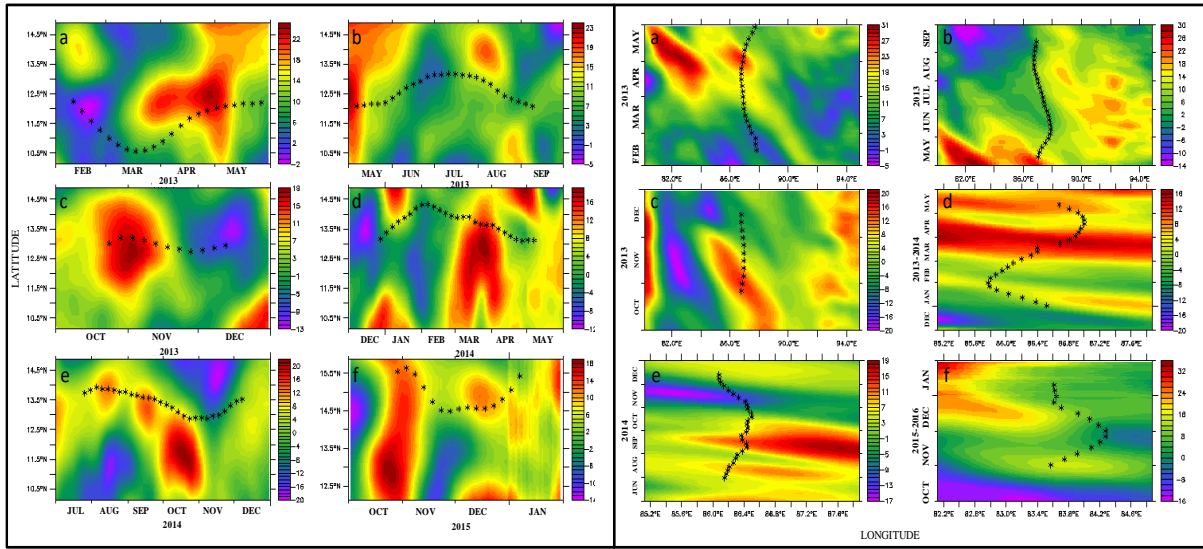


Figure 2:



**Figure 3:**

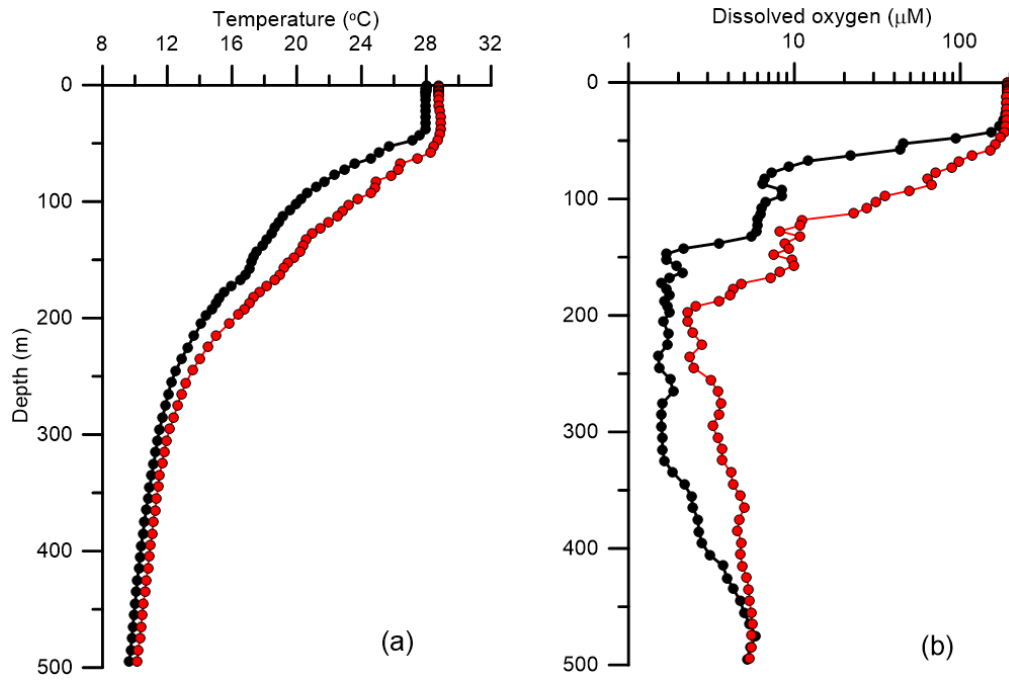


Figure 4

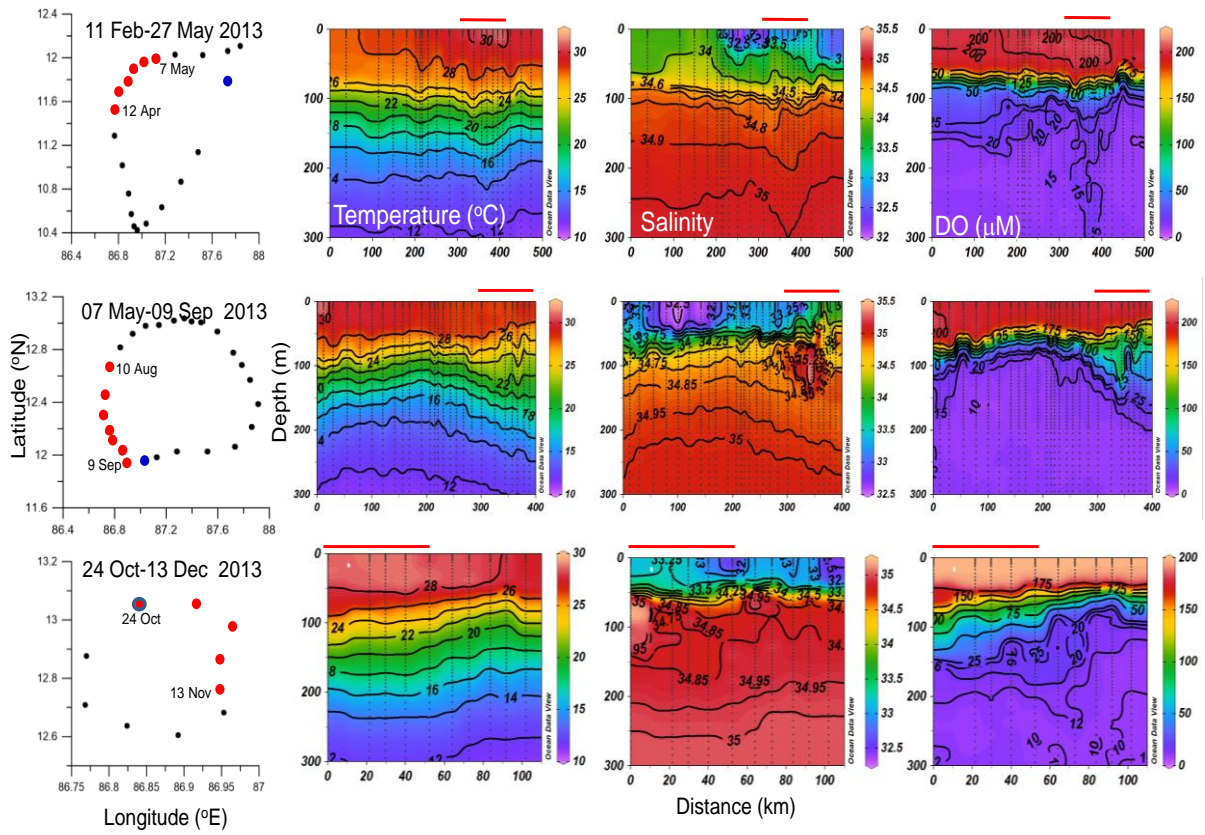
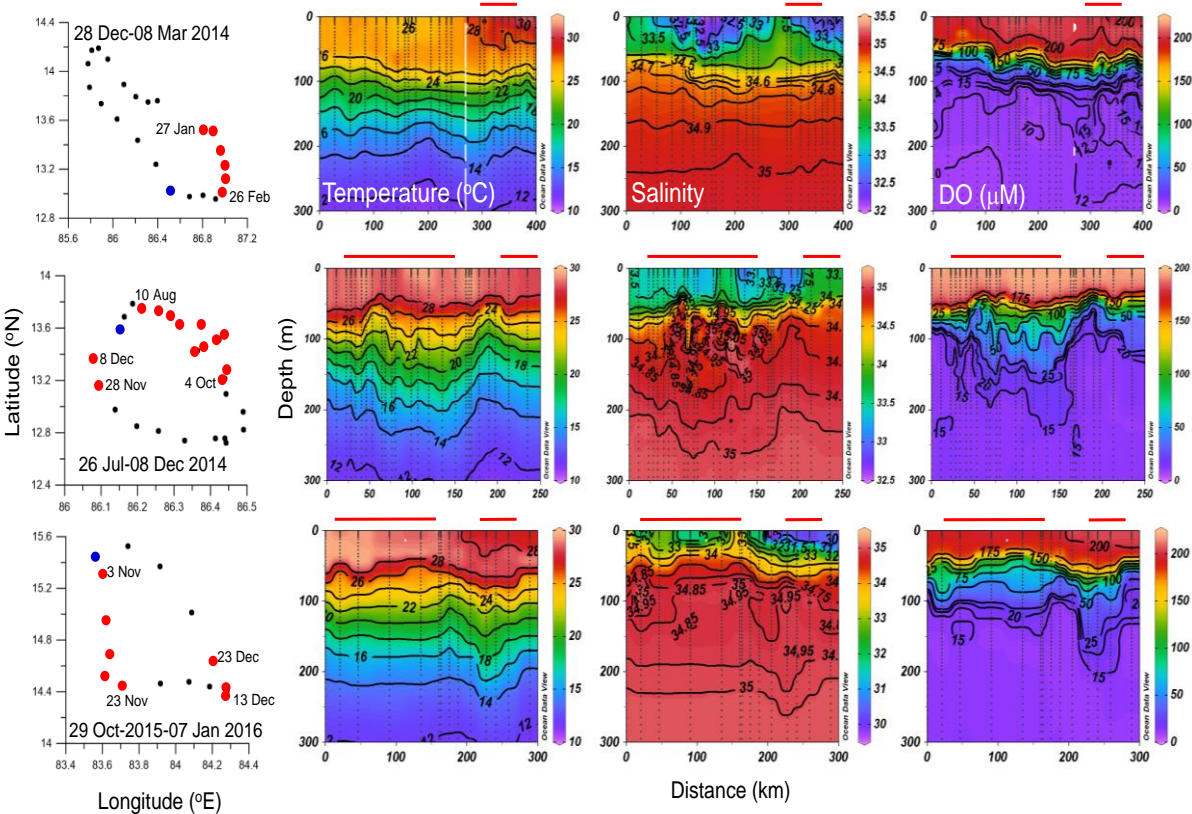


Figure 4: continued



**Figure 5:**

