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Responses of dissolved oxygen to Deep Depression BOB 04 based on satellite and Bio-Argo observations in the Bay of Bengal

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This work explores the responses of subsurface dissolved oxygen (DO) to "Wind Pump" impacts of Deep Depression (DD) BOB 04 (2014) with a pre-existing cyclonic eddy based on satellite and Bio-Argo observations in the central Bay of Bengal. Results show the combined influence of the pre-existing cyclonic eddy and DD BOB 04 shoaled the oxycline from 48 m to the shallowest depth 32 m two days after the DD BOB 04. With the pre-existing cyclonic eddy, BOB 04 induced DO decrease in the subsurface for a long time of 18 days. The strong saline stratification suppressed the chlorophyll enhancement along the DD track after its passage. However, this weak DD caused the significant subsurface DO decrease owing to the upwelling. This hovered DD with a pre-existing cyclonic eddy played an important role in governing the boundary of oxygen minimum zone.

[Keywords: Bay of Bengal, Cyclonic eddy, Dissolved oxygen, Upwelling, Oxygen minimum zone, Wind pump]

Introduction

In the global ocean, strong oxygen minimum zones (OMZ) are reported in the Arabian Sea, Bay of Bengal and Eastern Tropical Pacific. The occurrence of OMZ in the Bay of Bengal which occurs at intermediate depths (60-800 m)[1-3] was investigated in the past. When dissolved oxygen (DO) concentrations drop below ~60 to 120 μmol/kg, the mobile macro-organisms would be stressed or even die[4]. The animals live in a limited space in the upper layers of the Bay of Bengal.

In the Bay of Bengal, mesoscale cyclonic eddies are well known for the enhancement of the phytoplankton biomass. Roles of cyclonic eddy on transmission of nutrients to increase in primary and export productions were documented in the Bay of Bengal[5-7]. What's more, cyclonic eddy can induce the lower oxygen levels in the Bay of Bengal[8]. The cyclonic eddies shoal the boundary of OMZ, which has significant influence on OMZ[9]. In the Bay of Bengal, tropical cyclones (TCs) mainly occur in the pre-monsoon period (April – May) and the post-monsoon period (October – December). TCs can strengthen the intensities of cyclonic eddies when crossing over cyclonic eddies. The pre-existing cyclonic eddies would generate significant phytoplankton blooms and obvious cooling of sea surface temperature under the influence of TCs[10-12]. However, how the TCs "Wind Pump" affect the subsurface DO with a pre-existing cyclonic eddy in the Bay of Bengal has not been fully studied.

In the Bay of Bengal, the strong salinity stratification was induced by the freshwater influx from heavy precipitation and rivers, which limited the nutrient in this region. Hence, it can be considered as a region of low biological productivity[13]. Previous studies mostly focused on the "Wind Pump" impacts of strong TCs which often caused the serious phytoplankton blooms and obvious cooling in the Bay of Bengal[14, 15]. However, the "Wind Pump" impacts of weak TCs are generally neglected. In this work, we focused on a Deep Depression (DD) BOB 04 and tried to understand the physical processes on the temporal changes of DO with a pre-existing cyclonic eddy under this Deep Depression in the Bay of Bengal.

Data and Methods

Argo data

Three Bio-Argo floats were used in this work to explore temporal changes of DO in the subsurface layers of the Bay of Bengal during the passage of DD BOB 04. Temperature, salinity and chlorophyll a

(Chl-*a*) measurements from three Bio-Argo floats were used to investigate the subsurface hydrographic and biological responses to BOB 04. The three Bio-Argo floats are 5903712 (M), 2902086 (L) and 2902114 (R), respectively. These three floats measured vertical profiles (~5 m to 2000 m) of DO and hydrography with time intervals of five days or seven days. In this study, we chose the vertical profiles at depths from ~5 to 100 m. The Aanderaa Optode 4330 (DO sensors) were equipped on these three floats. The DO data had two levels of quality control and the calibration is ~5 % or 8 μM[16]. The hydrographic profiles of Bio-Argo floats were obtained from the International Argo Program at www.argodatamgt.org/.

Based on Argo data, the mixed layer depth (MLD) is defined as the depth at which the potential sea water density is 0.2 kg m^{-3} higher than the surface density[17]. In this work, we used the depth of 50 μmol kg^{-1} as the oxycline depth in the Bay of Bengal[18].

This work calculated static stability [E] in the upper 100 m layer[17] using

$$E = \frac{1}{\rho}\frac{\partial \rho}{\partial z} \qquad \ldots (1)$$

Where, ‘ρ’ is sea water density and ‘z’ is the depth taken as negative. The negative values of E indicate unstable water column, whereas the positive values indicate stratified water column.

Tropical cyclones and satellite data

DD BOB 04 was named by the India Meteorological Department (http://www.rsmcnewdelhi.imd.gov.in/), and it was also classified as tropical storm five according to the Joint Typhoon Warning Center. It formed over the central Bay of Bengal during 5-8 November 2014. It took a loop on 6 November and then turned westwards on 7 November. During its westward movement, it started weakening to a low pressure on 8 November (Fig. 1).

The storm track data of DD BOB 04 was obtained from India Meteorological Department. The translational speeds were estimated from time-varying positions of its storm center. Remote Sensing Systems (http://www.remss.com/) provide the sea surface temperature (SST, MW_IR) products with spatial resolution of 9 km. Daily sea level anomaly (SLA) was obtained from www.aviso.oceanobs.com. The daily rainfall with the resolution of 0.25°×0.25° was obtained at https://disc.gsfc.nasa.gov/. The 8-day MODIS chlorophyll was extracted from the NASA’s website at oceancolor.gsfc.nasa.gov/. The daily sea surface winds and wind stress vector $(\vec{\tau})$ with the resolution of 0.25°×0.25° were obtained from ftp.ifremer.fr/ifremer/cersat/products/gridded/MWF/L3/ASCAT/.

In this work, we used the surface wind stress vector $(\vec{\tau})$ to calculate the Ekman pumping velocity (EPV)[19]:

$$\mathrm{EPV} = -\mathrm{Curl}_z\left(\frac{\vec{\tau}}{\rho_0 f}\right) \qquad \ldots (2)$$

Where, ‘ρ_0’ is the sea water density (1025.0 kg m^{-3}) and ‘f’ is the Coriolis parameter.

Results

Satellite remote sensing data before and after DD BOB 04

The three-day average SSTs before, during and after DD BOB 04 are shown in Figure 2 (A). Before DD BOB 04 the SST was higher than 29 °C over the areas occupied by three Argos (Fig. 2 A-a). During the passage of BOB 04, the SST showed slight decrease about 0.5 °C (Fig. 2 A-b). Distributions of EPVs indicated that the wind-induced upwelling before the TC (02-04 November; Fig. 2 B-a) were weak over the areas occupied by three Argos. During the passage of TC on 05-07 November, the positive and large EPVs (greater than 0.2×10^{-4} m s^{-1}) occurred over the areas occupied by three Argos (Fig. 2 B-b).

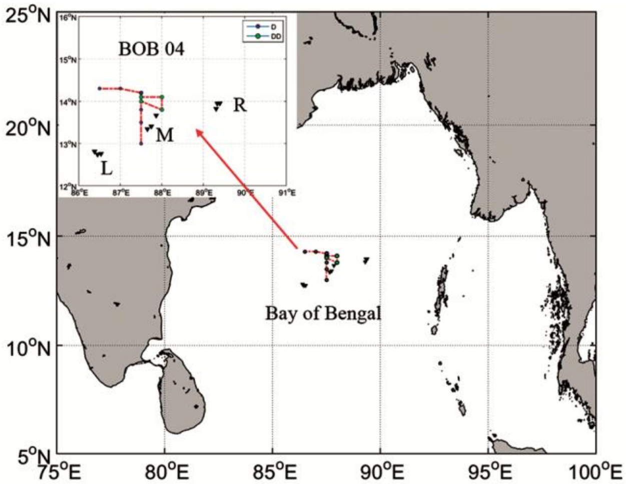

Fig. 1 — Map of the Bay of Bengal, storm track of Deep Depression BOB 4 and positions of three Argo floats. The storm track of Deep Depression BOB 04 and Argo positions are marked by red dashed lines and black triangles respectively. The 6 h positions of TC centers are marked by colored dots along the storm track, of which sizes and colors represent the TC intensity. D and DD represent depression, deep depression according to India Meteorological Department. L, M and R represent three Argos 2902086, 5903712 and 2902114.

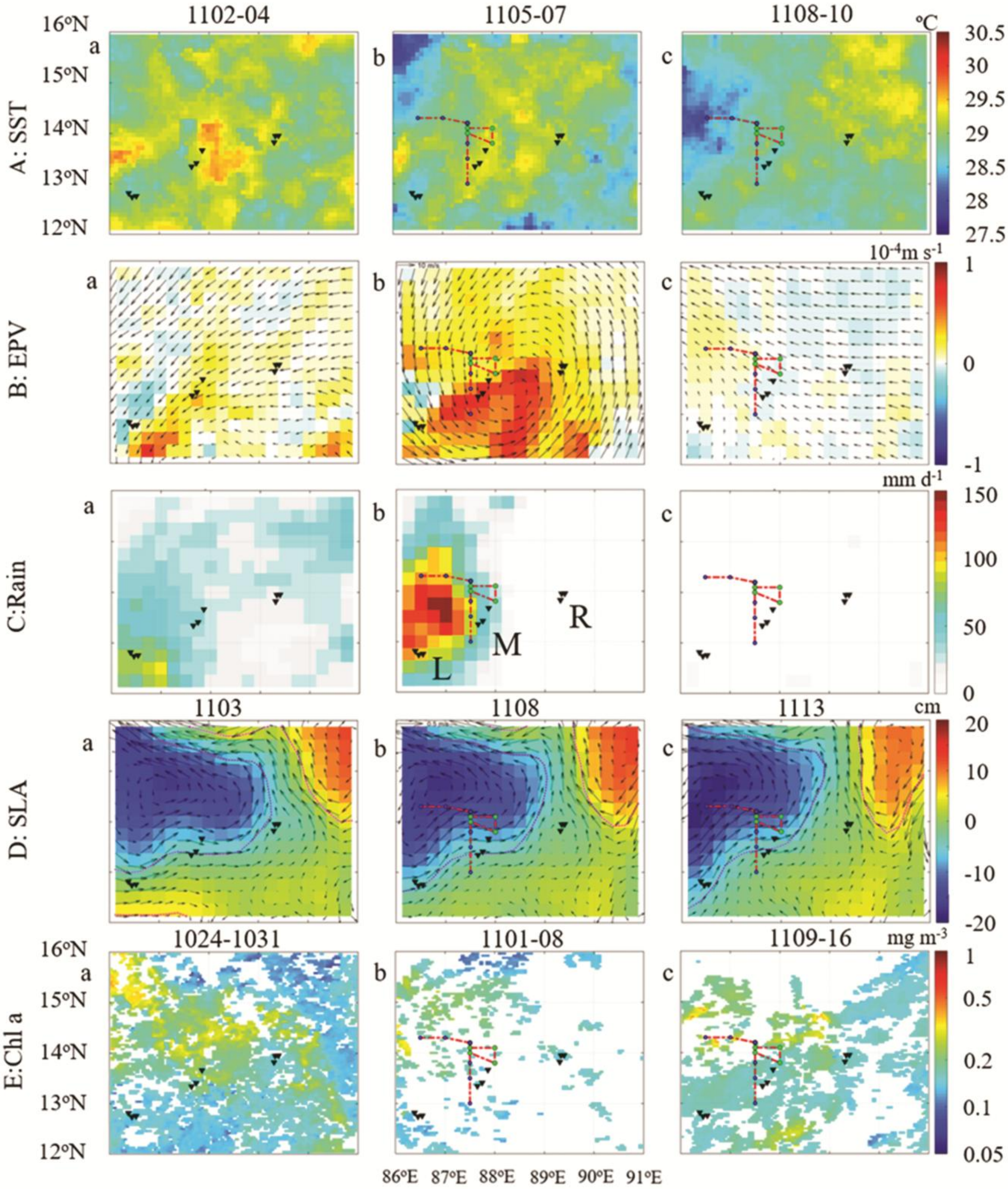

Fig. 2 ─ Satellite remote sensing data of A: surface sea temperature (SST, °C); B: Ekman pumping velocity (EPV, m s^{-1}) and wind speeds (m s^{-1}), C: rain (mm d^{-1}); D: sea level anomalies (SLA, cm) and absolute geostrophic currents at the sea surface (m s^{-1}) and E: Chl-*a* (mg m^{-3}) over the area under the influence of BOB 04. Left, middle and right are satellite data before, during, and after the passage of BOB 04. The inverted black triangles represent the Argo positions. Dashed lines and color dots represent the storm track and intensity of DD BOB 04.

These positive and large EPVs indicated the occurrence of strong storm-induced upwelling during the passage of BOB 04. After the passage of BOB 04, the EPVs were weak over three Argos (Fig. 2 B-c). The 3-day average wind speeds reached 8.4, 10.2, 7.4 m s^{-1} and EPVs were 0.7×10^{-4}, 0.3×10^{-4}, 0.2×10^{-4} m s^{-1}, respectively, over Argo_M, Argo_L and Argo_R from 5 to 7 November (Table 1). Three-day average distributions of rain show there were heavy rain over Argo_M and Argo_L before and during the passage of TC (especially more than 100 mm d^{-1} over Argo_L during TC; Fig. 2 C-b).

On 3 November, there was a cyclonic eddy (with negative SLA and anticlockwise geostrophic currents) before the passage of BOB 04 (Fig. 2 D-a). It should be noted that the cyclonic eddy was intensified and expanded its size on 8 November due to BOB 04 (Fig. 2 D-b). Argo_M moved northeastward during BOB 04 and it was located at the edge of the cyclonic eddy. Argo_L moved westward during and after BOB 04. The cyclonic eddy expanded its size to the Argo_L and it was located at the edge of the cyclonic eddy on 8 November (Fig. 2 D-b). The SLA over Argo_L decreased from -4 cm (3 November) to -6 cm (8 November) and to -9 cm (13 November). This indicates that the cyclonic eddy intensity over Argo_L was strengthened. Argo_R located between an anticyclonic eddy and the cyclonic eddy before TC, then moved northeastward after the passage of TC. The anticyclonic eddy weakened but moved close to the area occupied by Argo_R. Distributions of the surface Chl-*a* indicates the concentrations of Chl-*a* were closed to 0.2 mg m^{-3} before, during and after TC (Fig. 2 E). Therefore, BOB 04 did not induce the phytoplankton bloom in the surface waters.

Table 1 ─ Comparison of wind speed and Ekman pumping velocity (EPV) when Deep Depression (DD) BOB 04 was sweeping the Argos, the recorded time of Argos after BOB 04 passed, the mixed layer depth (MLD), the oxycline depth and static stability before and after BOB 04 and DO change after BOB 04

Argo floats	5903712 (M)	2902086 (L)	2902114 (R)
Wind speed(m/s)	8.4	10.2	7.4
EPV(10^{-4}m/s)	0.7	0.3	0.2
The recorded time after TC(day)	~2	~3	~4
MLD change (m)	8→19	39→36	17→19
The oxycline depth before and after TC (m)	48→32	67→58	62→47
Static stability before and after TC(10^{-4} m^{-1})	6→5.2	3.5→4	4.2→4.3
DO change	Decrease (7-82 m)	Decrease (7-91 m)	Decrease (14-73 m)

Observations in the upper 100 m by three Bio-Argos

Figure 3 presents the vertical distributions of temperature and salinity before, during and after BOB 04 over three Argos. Before the passage of TC, the depth of 26 °C (D26) isotherm over Argo_M was ~46 m, shoaled to ~31 m during TC, then restored to ~39 m after TC (Fig. 3 a). The D26 (> 60 m) of Argo_L and Argo_R were deeper than the value of Argo_M before TC, and shoaled during the BOB 04 (Figs. 3 b, c). It should be noted that the D26 of Argo_L was shallow and did not restore to the pre-storm values until 18 days after TC (Fig. 3 b). The salinity of these three Argos increased in the subsurface layers during the passage of TC. And the change of salinity of Argo_L was similar to the change of temperature, which restored at 18 days after TC. The variability of temperature and salinity indicates enhanced upwelling caused by BOB 04. The surface salinity over the areas occupied by these three Argos was significantly lower than the salinity of the subsurface waters (Figs. 3d, f). The heavy rain over Argo_L resulted in the decrease of salinity (Fig. 3e). The mixed layer depth (MLD) over Argo_M and Argo_R increased from 8-17 m before BOB 04 to 19 m after BOB 04 (Table 1). And the MLD over Argo_L decreased from 39 m to 36 m after the passage of BOB 04. The decrease of MLD and the shallow MLD of three Argos indicate that the storm-induced mixing was weak and the mixing mainly affected the waters in the top 40 m. The water column static stability was more than 3.5×10^{-4} m^{-1} before BOB 04 which reveals the serious saline stratification in the upper 100 m of water column (Table 1). After the passage of BOB 04 the static stabilities were also higher than 4×10^{-4} m^{-1}. Hence, BOB 04 did not break the thick saline stratification to bring the deep waters to the shallow layers.

Figure 4 presents the vertical distributions of DO and Chl-*a* before and after BOB 04 over three Argos. The observed DO concentrations dramatically decreased at depths 7-82 m, 7-91 m and 14 - 73 m of Argo_M, Argo_L and Argo_R at 2 - 4 days after BOB 04 respectively (Table 1). The oxycline depths measured by Argo_M, Argo_L and Argo_R were 48, 67 and 62 m before TC, and then shoaled up to 32, 58 and 47 m at 2-4 days after TC respectively. The similar phenomenon to the temperature was that the observed DO concentrations decreased and did not restore to the pre-storm values until 18 days after TC (23 November) over Argo_L. These changes show a continuous upwelling which brought the low temperature, high salinity and low-oxygen waters in

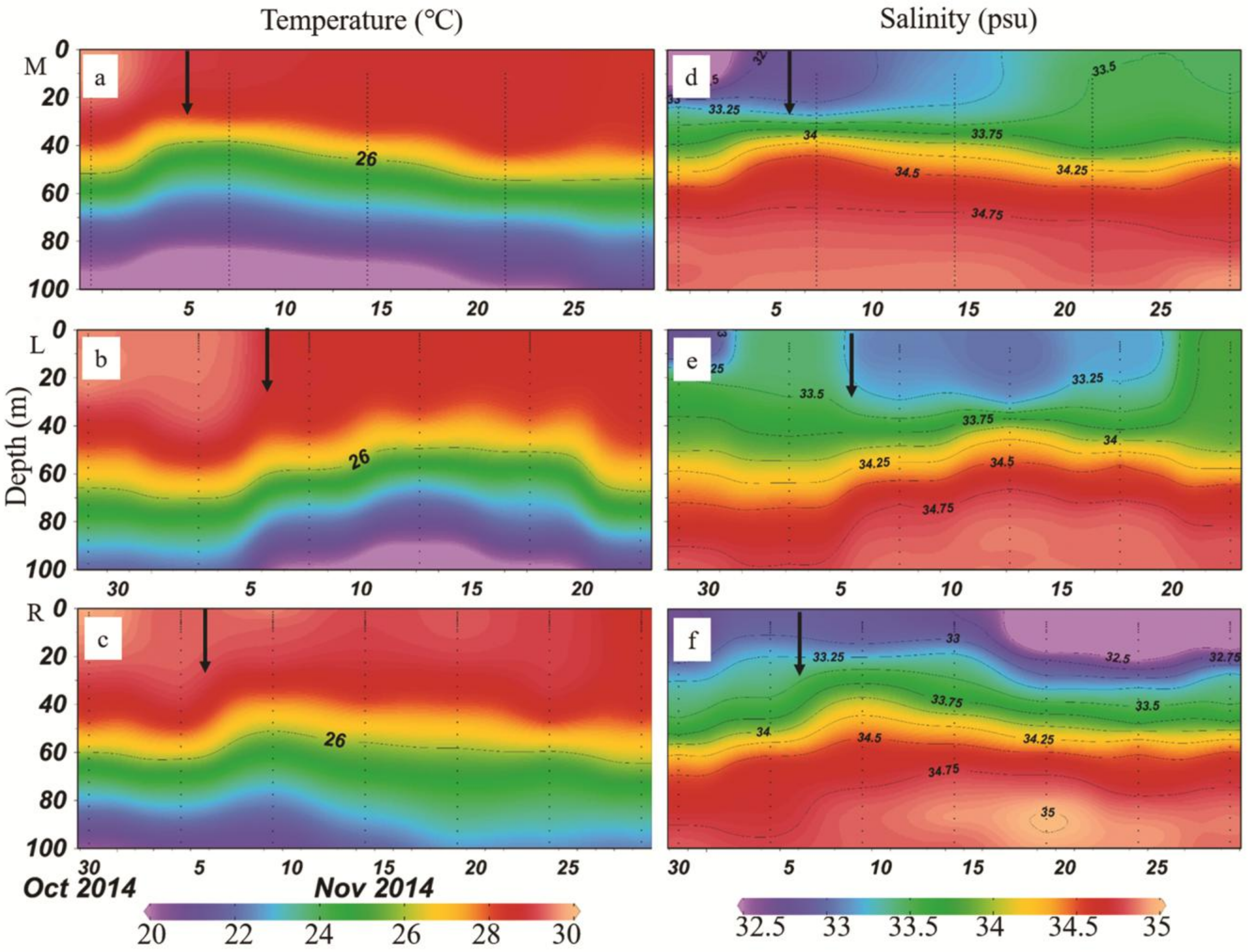

Fig. 3 ─ Vertical profiles of temperature (ºC) and salinity (psu) in the upper 100 m from three Bio-Argo floats. The black arrows represent the day when TC was passing.

the deep subsurface to the shallow subsurface during BOB 04. Furthermore, we calculated the integrated DO in the upper 100 m. The integrated DO over Argo_M was 7.24 µmol m^{-2} before the passage of BOB 04, declined to 4.51 µmol m^{-2} (07 November) and then restored to 6.05 µmol m^{-2} (14 November; Fig. 5 a). The integrated DO over the area occupied by Argo_L was 9.36 µmol m^{-2} before the passage of BOB 04, declined to 7.40 µmol m^{-2} (08 November) but continuously declined to 6.02 µmol m^{-2} (13 November). The integrated DO over Argo_R was 8.60 µmol m^{-2} before the passage of BOB 04, declined to 6.31 µmol m^{-2} (09 November) but significantly increased to 9.02 µmol m^{-2} (14 November).

Figures 4 (d, e) depict the vertical profiles of Chl-*a* in the top 100 m. Unfortunately, there was no data of Chl-*a* over Argo_M. The subsurface chlorophyll maximum value (SCM) was high before the passage of BOB 04 (1.33 mg m^{-3} at 62 m over Argo_L on 03 November; 1.06 mg m^{-3} at 53 m over Argo_R on 04 November). During the passage of BOB 04, the depth of SCM over Argo_L was significantly uplifted to 48 m and the SCM decreased to 0.49 mg m^{-3} on 07 November. The depth of SCM over Argo_R was elevated to 42 m and the SCM increased to 1.37 mg m^{-3}. The Chl-*a* between 0 and 30 m slightly increased to ~0.25 mg m^{-3} over Argo_L which was close to the value of remote sensing data. After the passage of BOB 04, the SCM gradually restored and the depth of SCM also recovered to the pre-storm level. To further demonstrate the production of Chl-*a* in the upper 100 m, the integrated Chl-*a* was calculated. The results show the integrated Chl-*a* over Argo_L was 35.95 mg m^{-2} before the passage of BOB 04 (03 November), and decreased to 28.77 mg m^{-2} on 08 November. After the passage of BOB 04, the integrated Chl-*a*

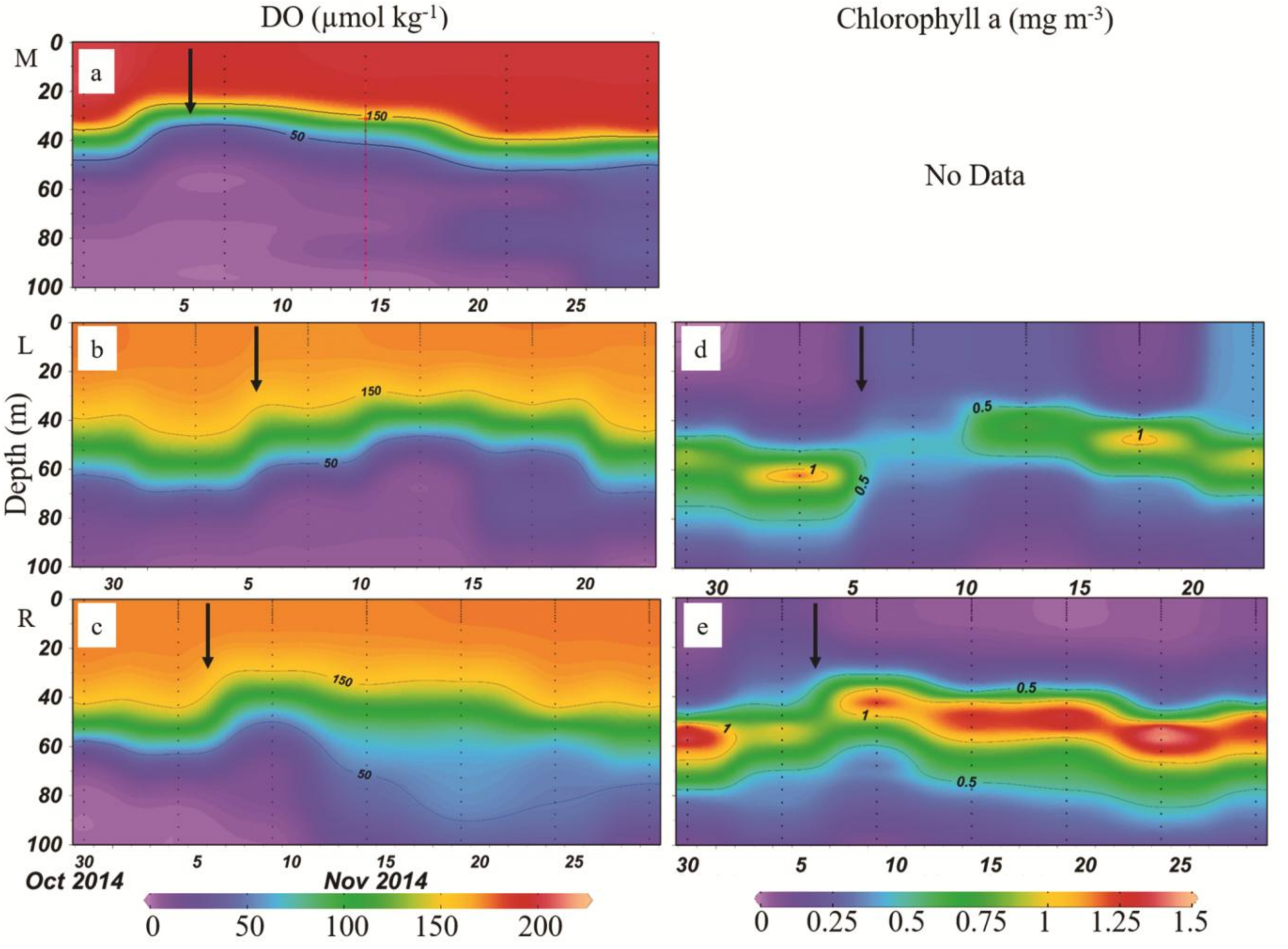

Fig. 4 — Vertical profiles of DO (μmol kg^{-1}) and Chl-*a* (mg m^{-3}) in the upper 100 m from three Bio-Argo floats. The black arrows represent the day when TC was passing.

gradually restored to 30.64 mg m^{-2} on 13 November. For Argo_R, the integrated Chl-*a* in the top 100 m was 40.02 mg m^{-2} on 04 November, and slightly decreased to 39.06 mg m^{-2} on 08 November (Fig. 5b). At 9 days after the passage of BOB 04, it increased to 45.63 mg m^{-2} on 14 November. In total, phytoplankton bloom did not occur over the two Argos. The phytoplankton changes were mainly attributed to the storm-induced upwelling.

Discussion

The effect of DD BOB 04 on DO variability

Previous studies documented physical processes control the boundary of OMZ and biological processes govern the absolute DO concentration in the OMZ[8,9,20,21]. The "Wind Pump" impacts of storm induced intense vertical mixing and upwelling, which determine the vertical movement of the thermocline and then change the boundary of the OMZ. In addition, owing to the storm-induced mixing and upwelling, TC would bring the deep subsurface waters with rich nutrients to the shallow layers to stimulate the phytoplankton growth. Chen and Tang[22] reported a looped TC Linfa induced obvious phytoplankton bloom in the South China Sea. However, according to the Chl-*a* of Bio-Argos and the remote sensing data, this DD did not induce the phytoplankton bloom for two main reasons. Firstly, the wind intensities of DD BOB 04 were weak (≤ 10.2 ms^{-1}), therefore the storm-induced mixing was not strong. Secondly, the high positive values of static stability showed the water columns in the top 100 m were highly stratified. The waters with low salinity were in the top 40 m. Therefore, the weak BOB 04 couldn't break the thick saline stratification and transport the rich nutrients waters to the shallow

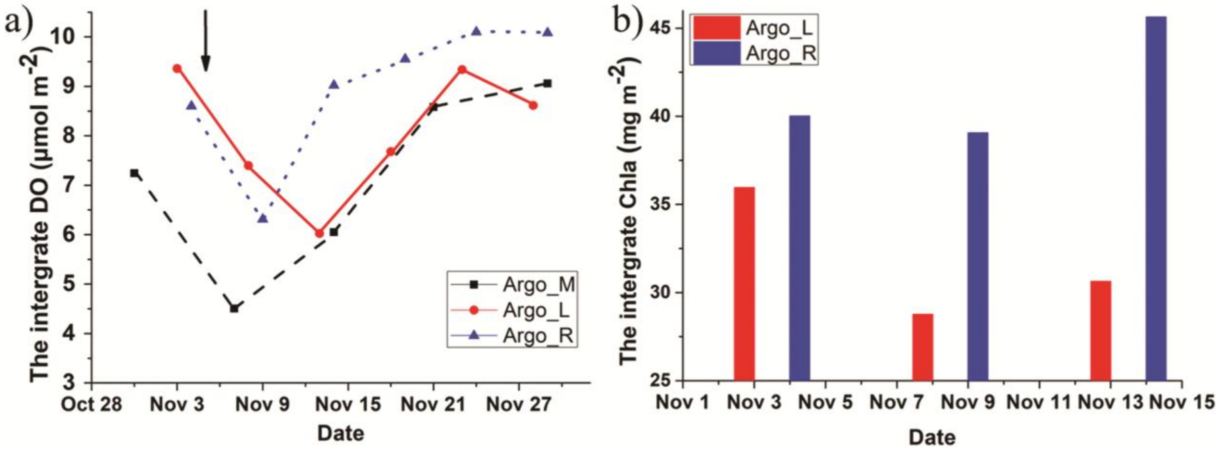

Fig. 5 ─ Time series of the integrated DO (µmol m^{-2}) and Chl-*a* (mg m^{-2}) in the upper 100 m observed by three Bio-Argo floats. The black arrows represent the day when TC was passing.

layers to promote the phytoplankton growth. When BOB 04 was passing over this region, the average translational speed was ~2.11 ms^{-1}. When the storm's translational speed was slow-moving (≤ 4 ms^{-1}), storm can evoke strong upwelling in the relaxation stage[23]. What's more, BOB 04 hovered over this region for three days. DD BOB 04 can be considered as a near stationary storm which had the enough forcing time available to lead the strong upwelling[24, 25]. The EPVs of BOB 04 and the variability of temperature and salinity in the top 100 m show the strong upwelling. The obvious DO decrease occurred at depth about 30-60 m and the shallow subsurface layer (0-30 m) had a small variability. In total, the phytoplankton bloom did not occur in this region. Hence, the physical processes (mainly upwelling) induced by the "Wind Pump" impacts of BOB 04 resulted in the change of DO decrease. This DD shoaled the oxycline and uplifted the boundary of the OMZ, which would compress vertical habitat and shoal the distributions of fishery species and their prey.

The effect of eddies on the variability of DO

The mesoscale eddies (both anticyclonic and cyclonic eddy) have significant impacts on OMZ[9]. The previous research found the cyclonic eddy can cause the lower oxygen levels in the Bay of Bengal[8]. Anticyclonic eddies transport the rich-oxygen waters in the surface to the subsurface layers, which lead to weakening of OMZ[21]. In this work, there was a pre-existing cyclonic eddy under the influence of DD BOB 04 and the intensity of this eddy was strengthened. This pre-existing cyclonic eddy had significant influence on the DO variability. For Argo_M, before BOB 04, it was located in the cyclonic eddy (Fig. 2). Owing to the eddy-induced upwelling, the oxycline and the integrated DO of Argo_M were lower than another two Argos which were located out the cyclonic eddy (Fig. 4). Previous study found that a pre-existing cyclonic eddy generated the large upwelling owing to the "Wind Pump" of cyclone intensification[26]. Moreover, the EPV over the area occupied by Agro_M was higher than others; therefore the oxycline after BOB 04 was shoaled to 32 m which was much shallower than the values of another two Argos (58 m for Argo_L and 47 m for Argo_R). It should be noted that under the influence of BOB 04, the cyclonic eddy moved southwest and the intensity over Argo_M was gradually weakened. However, the cyclonic eddy moved to the Argo_L and the intensity of eddy over the area occupied by Argo_L was gradually strengthened. Due to this strengthened cyclonic eddy, it would generate a large upwelling to transport the low oxygen waters to the shallow layers. Hence, after the passage of BOB 04, the continuous DO decrease resulted from the strengthened cyclonic eddy. Except for this cyclonic eddy, there was an anticyclonic eddy in the northeast of the BOB 04. The anticyclonic eddy gradually moved southwest and closed to the Argo_R (Fig. 2D). Due to the ventilation of the anticyclonic eddy, the DO of the deep subsurface layers increased[21]. The movement of this anticyclonic eddy brought the high DO waters to the Argo_R, so the integrated DO in the upper 100 m was higher than the pre-storm level (Fig. 4c).

Conclusion

This work explores how the "Wind Pump" of DD BOB 04 affected the DO with a pre-existing cyclonic eddy over the OMZ in the Bay of Bengal based on satellite and Bio-Argo data. This hovered DD did not induce the phytoplankton bloom, but it induced the strong upwelling which resulted in the DO decrease in the subsurface layers. The pre-existing cyclonic eddy was strengthened by the "Wind Pump" of DD BOB 04, which induced the DO decrease for a long time in the subsurface. The movement of an anticyclonic eddy brought the high DO waters to facilitate the recovery of the DO decline.

Acknowledgments

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Conflict of interest

The authors declare that they have no competing or conflict of interest to influence the work reported in this paper.

Author Contributions

Conceptualization, Investigation, Writing - original draft, review & editing: HBX, DLT; Formal analysis, Resources and Software: HBX; Funding acquisition and Supervision: DLT.

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