

Response of micro- and mesozooplankton in the southwestern Bay of Bengal to a cyclonic eddy during the winter monsoon, 2005

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Abstract A cyclonic eddy (CE) in the southwestern Bay of Bengal (SWBoB; 10–15° N; 81–87° E) during winter monsoon 2005 and associated changes in the open ocean hydrography and productivity patterns were studied using satellite observations and in situ measurements. Analysis of the satellite-derived sea surface height anomaly (SSHA) indicated the existence of a large eddy (10–15° N; 81–87° E) from November to January, with its core centered at 13° N and 82° E. The large positive wind stress curl ($\sim 1.8 \times 10^{-7} \text{ N m}^{-2}$) and resultant Ekman pumping ($\sim 3 \times 10^{-2} \text{ cm s}^{-1}$) were identified as the prominent forcing mechanisms. In addition, the cyclonic storms and depressions experienced in the region during the study period seem to have served to maintain the strength of the CE through associated Ekman pumping. The cold ($\sim 26.6^\circ \text{C}$), nutrient-enriched ($\text{NO}_3 > 2 \mu\text{M}$, $\text{PO}_4 > 0.73 \mu\text{M}$ and $\text{SiO}_4 > 3 \mu\text{M}$) upwelled waters in the upper layers of the CE enhanced the biological production ($\text{chl. } a > 0.56 \text{ mg m}^{-3}$). Dissolved oxygen in the surface waters was $> 200 \mu\text{M}$. The phytoplankton and zooplankton biomass recorded during the season was comparable or perhaps higher than the peak values reported from

the northeastern Arabian Sea (chlorophyll *a* concentrations of 0.2 to 0.4 mg m^{-3} and zooplankton biovolume 0.6 ml m^{-3}) during winter. Occurrence of a higher mesozooplankton biovolume (0.8 ml m^{-3}) and relatively low abundance of microzooplankton indicates the prevalence of a short food chain. In conclusion, high biological production, both at primary as well as secondary level, suggests the prevalence of an efficient food web as a result of physical forcing and subsequent ecological interactions evident up to tertiary level in an oligotrophic basin like BoB.

Keywords Cyclonic eddy · Mesozooplankton · Bay of Bengal

Introduction

The Bay of Bengal (BoB) is a unique tropical basin, situated in the eastern part of the northern Indian Ocean, occupying an area of 6 % of the world oceans. The oceanographic characteristics of this basin exhibit seasonality due to semi-annually reversing monsoon winds and currents (Schott and McCreary 2001; Shankar et al. 2002). The basin receives large quantity of fresh water through river runoff from Brahmaputra, Ganges, Mahanadi, Godavary, Krishna and Cauvery rivers and precipitation (200–240 cm year^{-1}). Annual runoff is computed as $1.625 \times 10^{12} \text{ m}^3 \text{ year}^{-1}$ (Subramanian 1993), and excess precipitation over evaporation is $\sim 2 \text{ m year}^{-1}$ (Prasad 1997). Dispersal of fresh water over the basin leads to low-saline upper water column with strong

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stratification throughout the year. Along with this, extensive cloud cover, sediment load and narrow shelf (Qasim 1977; Sengupta et al. 1977; Radhakrishna et al. 1978; Gomes et al. 2000) makes the basin relatively less productive than its western counterpart Arabian Sea. In contrast to Arabian Sea, major physical processes like coastal upwelling, winter convection, etc. are not active; instead, episodic events like eddies and gyres make the region locally productive.

Studies on biological production of the basin were carried out as part of major programmes viz., International Indian Ocean Expedition (IIOE), Marine Research-Living Resources (MR-LR) and Bay of Bengal Process Studies (BoBPS). Recent studies suggest that eddies and gyres have a promising role in governing the biological production of the oligotrophic bay, by influencing the vertical transport of nutrients to the photic zone (Prasannakumar et al. 2004, 2007, 2010; Vinayachandran et al. 2005; Muraleedharan et al. 2007; Fernandes 2008; Ramaiah et al. 2010; Fernandes and Ramaiah 2013, 2014; Sabu et al. 2015). Most of these studies deal with the influence of episodic events on the biological production, particularly in primary level (Prasannakumar et al. 2004, 2007, 2010; Vinayachandran et al. 2005; Ramaiah et al. 2010).

In the secondary level, planktonic components such as micro- and mesozooplankton play a key role in the marine food web by occupying an intermediate position between the primary and tertiary levels. Their distribution, abundance and community composition depend on the physical and biological processes, either together or independently (Haury et al. 1978). Hence, the spatial and temporal scales of variations in atmospheric as well as oceanographic conditions determine heterogeneity in zooplankton population and in turn the food web structure (Parsons 1980). Recently, few studies have documented the zooplankton response to the various physicochemical processes in the BoB (Muraleedharan et al. 2007; Fernandes 2008; Fernandes and Ramaiah 2013, 2014). Muraleedharan et al. 2007 emphasized the importance of basin scale (warm gyre) as well as meso-scale process (eddy and upwelling) in the biological production (both primary and secondary) during the summer monsoon. Although these studies highlight the impact of eddies on zooplankton community, trophic response of such events is least studied until date. In view of this, the present study describes the impact of a large cyclonic eddy on the planktonic structure, in the SWBoB during winter 2005.

Materials and methods

Data for the present study samples were collected on-board the *FORV Sagar Sampada* during the winter monsoon (December 2005) along the SWBoB (Fig. 1). Seabird CTD (SBE 911 Plus) was used to collect vertical profiles of temperature and salinity in the upper 1000-m water column. Salinity values from CTD were corrected against the values derived from the Autosal (Guild line 8400) on-board. The sea surface temperature (SST) was measured using a bucket thermometer. The mixed layer depth was determined as the depth where the density difference from the sea surface was 0.2 kg m^{-3} (Shetye et al. 1996). The thermocline layer was demarcated as the depth at which the temperature reached $15 \text{ }^{\circ}\text{C}^1$.

Water samples were collected using Niskin bottles from 11 standard depths (viz. 0, 10, 20, 30, 50, 75, 100, 150, 200, 250 and 300 m (Sverdrup et al. 1942)) for the estimation of dissolved oxygen (DO) and nutrients. DO was estimated by the Winkler method (Strickland and Parsons 1972) and nutrients (Grasshoff et al. 1983) by Auto-Analyzer (SKALAR) on-board *FORV Sagar Sampada*. For the estimation of chlorophyll-*a*, 1 l of water sample was collected from 7 standard depths (surface, 10, 20, 50, 75, 100 and 120 m) and filtered through a GF/F filter (pore size 0.7μ). Chlorophyll-*a* was extracted with 10 ml of 90 % acetone and analysed spectrophotometrically (Perkin-Elmer UV/Vis at 640 nm) (Strickland and Parsons 1972). Total column (upper 120 m) chlorophyll *a* (mg m^{-2}) concentrations were estimated by integrating the profile values.

For estimating microzooplankton, 5–8 l of water sample was collected from 7 standard depths (surface, 10, 20, 50, 75, 100 and 120 m). Water samples were initially prefiltered through a 200- μm bolting silk (Hydro-Bios) to eliminate the mesozooplankton, and the filtrate was carefully collected into black polythene bottles and fixed in 3–8 % of acid Lugol's iodine. Although the screening of samples through a 200- μm sieve may disturb large and fragile mesozooplankton, this process is widely used in MZP sampling for discarding the mesozooplankton (Froneman and

¹ Thermocline layer is a zone of rapid increase in temperature, ending in a colder and relatively constant-temperature deeper layer (Levinton 1995). In our study area, the thermocline layer is demarcated from the bottom of the mixed layer to the depth at which $15 \text{ }^{\circ}\text{C}$ isotherm is observed. Below this, the temperature remains relatively constant.

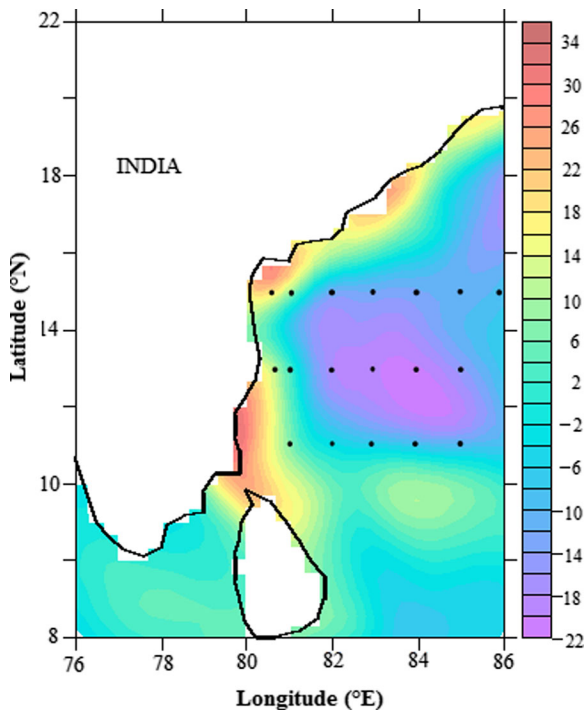


Fig. 1 Map shows the study region and sampling locations (*background colour* represents the sea surface height anomaly (cm) during November 2015. The *pink colour* represents the cyclonic eddy region)

McQuaid 1997; Putland 2000; Stelfox–Widdicombe et al. 2004). These samples were then concentrated by gravity settling and siphoning methods. The organisms present in the samples were identified and categorized into heterotrophic dinoflagellates (HDS), ciliates (CTS), sarcodines (SDS), and crustacean nauplii (CNP) (Kofoid and Campbell 1939; Marshall 1969; Steidinger and Williams 1970; Subrahmanyam 1971; Maeda and Carey 1985).

Mesozooplankton were collected using Multiple Plankton Net (MPN, HYDRO - BIOS, 0.25 m² mouth area, 200-µm mesh size). The net was towed vertically through five strata: the upper mixed layer, thermocline layer, bottom of thermocline to 300, 300–500 and 500–1000 m at a speed of 1 ms⁻¹. The mesozooplankton biovolume was calculated by the displacement volume method (Postel et al. 2000) and was preserved in the 4 % formalin–seawater solution for detailed examination in the shore lab. The sample was primarily sorted into various taxonomic groups based on published references (ICES 1947; Newell and Newell 1973; Todd and Laverack 1991). Zooplankton abundance was estimated by counting all the individuals present in the sample or

the aliquot depending on the volume. All abundance data were converted to density (ind.m⁻³) using the volume of water filtered by the net.

In addition to the in situ data, monthly averaged sea surface height anomaly (SSHA) from AVISO (<http://www.aviso.oceanobs.com>) and monthly mean chlorophyll data from MODIS (<http://www.oceancolor.gsfc.nasa.gov>) were also used.

Results and discussion

Thermohaline structure along 11° N, 13° N and 15° N showed a doming feature between 81° E and 83° E, especially in the upper 300 m (Fig. 2a, b and c). The intensity of the doming was at a maximum along 13° N with a vertical displacement of 25 °C isotherm from 60 m to surface (Fig. 2b). This doming feature in the thermohaline structure showed the presence of a large, intense cyclonic eddy (CE) in the study area. The weekly average SSHA along with geostrophic currents during the study period (December) confirmed the presence of a large CE centred at 13° N and 82° E, embedded in a large cyclonic circulation (90 cm s⁻¹) between 80° and 85° E and 10° and 18° N belt (Fig. 3). The presence of an intense CE in the southwest BoB during winter, 2005, has been reported earlier (Chen et al. 2013). The monthly mean SSHA from November 2005 to February 2006 shows that this CE formed in November 2005 is a part of a large cyclonic gyre (CG, Fig. 4). The CG then intensified as an eddy and became centred more towards the southern side of the BoB during December. The presence of a CG in the SWBoB during the northeast monsoon has been reported earlier (Vinayachandran and Yamagata 1998; Schott and McCreary 2001).

The CE is forced primarily by upward Ekman pumping (EP) caused by positive wind stress curl and resultant upwelling within this gyre, cooling the sea surface (Vinayachandran and Mathew 2003). In order to illustrate the role of wind stress and EP, the 3 days mean wind from July to December 2005 in the CE region was analysed. It can be seen that wind stress curl showed noticeable variation between October and December (Fig. 5). The observed positive wind stress curl in the CE region suggests that local wind stress curl is the dominant driving force behind the formation of CE. The figure also illustrates the associated positive Ekman velocity (green-line) representing upward motion or condition for upwelling. The low-frequency

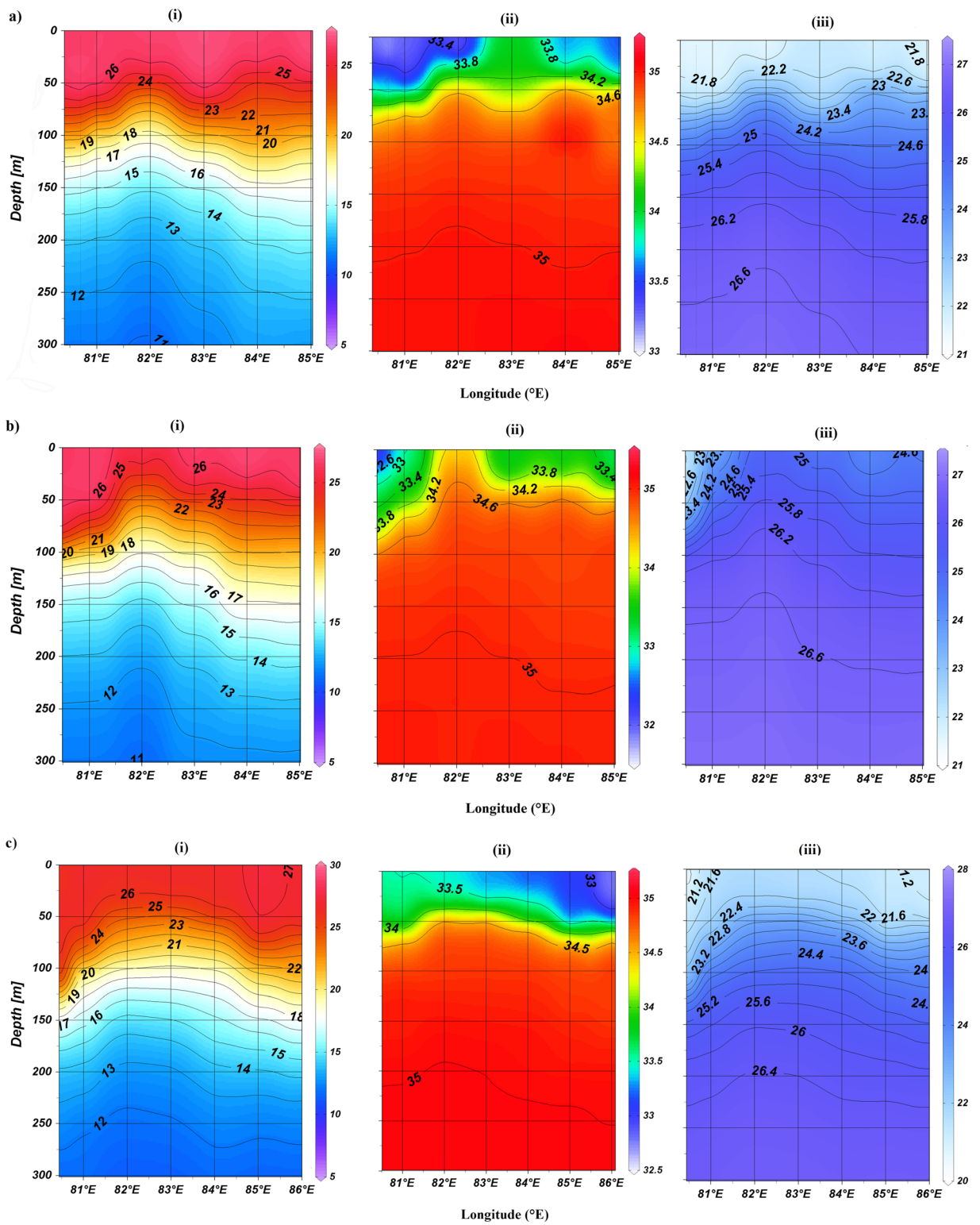


Fig. 2 Vertical distribution of (i) temperature (°C), (ii) salinity and (iii) density along (a) 11° N, (b) 13° N and (c) 15° N during the study period

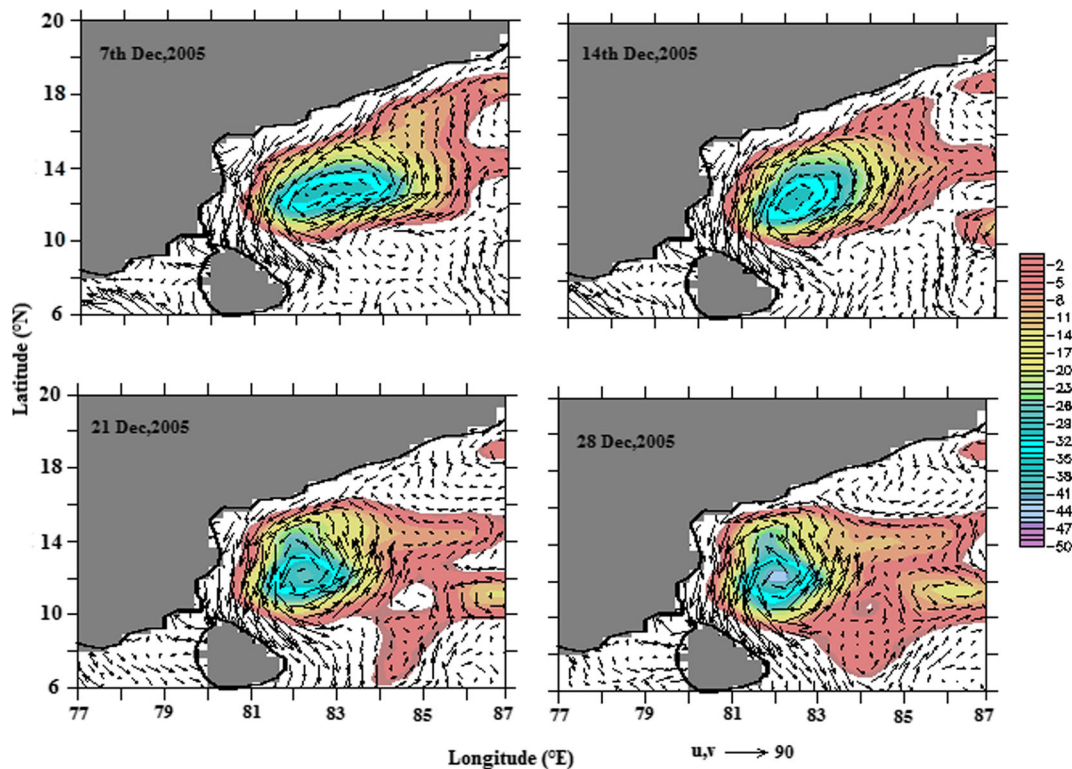


Fig. 3 Weekly SSHA (cm) overlaid with geostrophic current (cm/s) during the study period

variability of the wind stress has induced strong Ekman pumping producing a divergence in the upper water column, which may result in upward movement of deep water to the surface. This short-term variability of wind in the CE region was due to frequent cyclones and depressions occurring in the BoB (Fig. 6). During November–December, 2005 two cyclonic storms (‘BAZZ’—28 November to 2 December and ‘Fanoos’—6 to 10 December) and two depressions (20 to 22 November and 15 to 22 December) were experienced in the southern BoB. The wind stress curl ($\sim 12 \times 10^{-7} \text{ Nm}^{-3}$) and Ekman velocity ($\sim 32 \times 10^{-3} \text{ cm s}^{-1}$) increased significantly in the first week of December with the passage of these two tropical cyclones (Fig. 5).

To explore further the forcing mechanisms behind the intensification of the CE, the monthly mean SSHA along with geostrophic currents during 2004, 2005 and 2006 for the month of December (Fig. 7) were analysed. It was observed that the intensity of the East India Coastal Current (EICC) was anomalously stronger in 2005 ($>75 \text{ cm}^{-1}$) than 2004 ($<25 \text{ cm}^{-1}$) and 2006 ($<20 \text{ cm}^{-1}$). Also, the year 2005 was found to be a negative Indian Ocean dipole (IOD) year (Grunseich

et al. 2011); hence, the intensification of the EICC is due to the combined effect of intense eastward Wyrtki jet, strong summer monsoon currents and warm SST anomalies in the eastern equatorial Indian Ocean (EEIO) associated with negative IOD (Thompson et al. 2006). Hence, the increased number of cyclones/depressions in the study area and appreciable changes in the climatological circulation patterns in the EEIO appear to be linked to the IOD, in that a negative IOD made the CG more intense and active in winter 2005.

The distribution of dissolved oxygen (DO) and micronutrients in the upper waters showed prominent variability as a result of cyclonic eddy. The surface waters were well oxygenated ($>200 \mu\text{M}$) with an enhanced level of nitrate concentration ($\sim 2 \mu\text{M}$; Fig. 8) in the CE region. The dissolved oxygen (DO) and nitrate concentration varied from 200 to 233 μM and 1.1 to 3.8 μM , respectively, with a maximum at the centre of the CE. The average concentrations of DO and nitrate in surface waters recorded were 217 and 2.12 μM , respectively. Vertical profiles showed upsloping of isolines from subsurface (50 m) to surface along 13° N and 15° N, while along 11° N, the upsloping feature was relatively less prominent and restricted to the upper

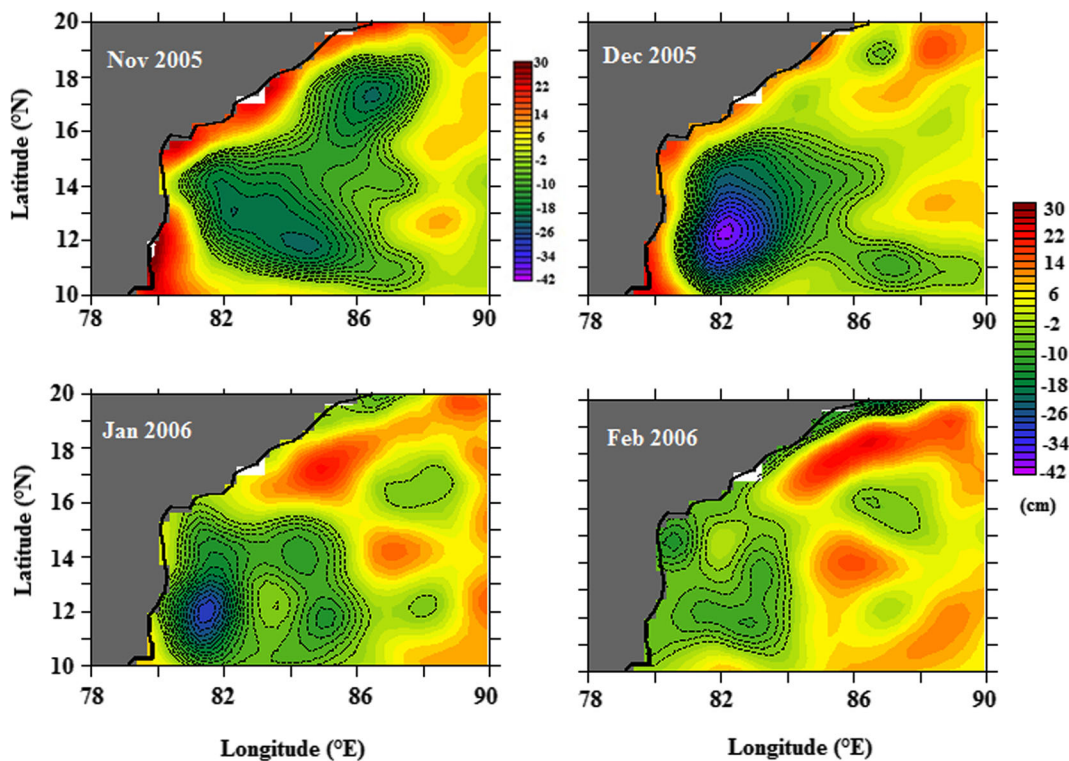


Fig. 4 Monthly mean SSHA (cm) variability over the Bay of Bengal. *Contours* represent negative SSHA in the study area from November 2005 to February 2006

50 m (Fig. 9). The strong Ekman pumping due to frequent cyclonic events in the BoB resulted in the upwelling of nutrient-enriched subsurface waters to the surface. The unusual nutrient enrichment in the photic zone may trigger the proliferation of phytoplankton, which liberates sufficient amount of dissolved oxygen to the surrounding waters as a result of photosynthetic activity. Supply of nutrients to the photic zone from the deep through Ekman pumping due to atmospheric and

physical forcing is a common phenomenon of nutrient transport in the basin, like BoB (Prasannakumar et al. 2004; Muraleedharan et al. 2007; Maneesha et al. 2011). The amount of nutrient entrainment depends on the strength as well as spatial and temporal variability of such mesoscale processes. In the present study, persistent and strong Ekman transport due to CE, along with successive physical events such as cyclones, depression and deep depression (Chen et al. 2013), provided

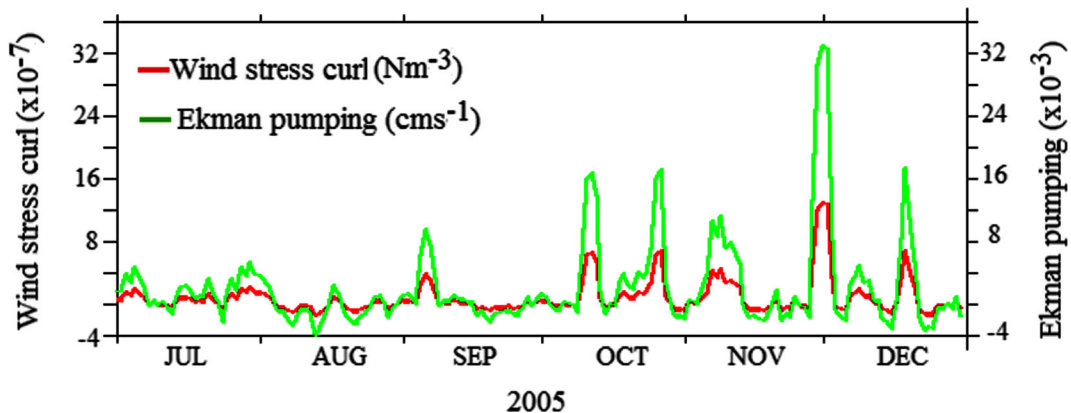


Fig. 5 Three-day mean wind stress curl (Nm^{-3}) and Ekman pumping in the CE region (cm s^{-1})

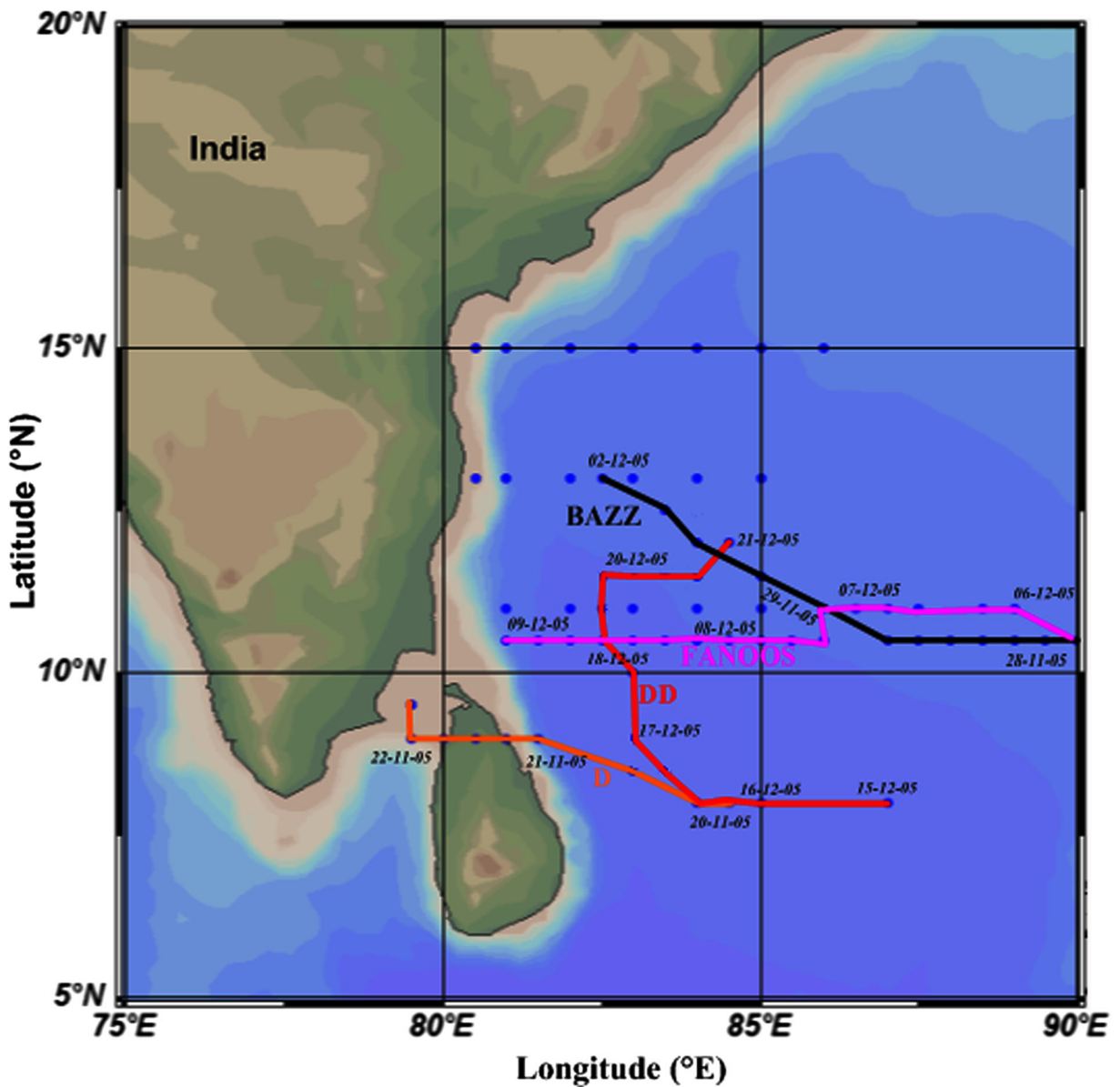


Fig. 6 Station locations and the track of depressions and storms. The pink line represents the track of FANOOS, the black line represents the track of BAZZ, the red line represents the track of deep depression and the orange line represents the track of depression

sufficient amount of nutrients to the photic zone to trigger phytoplankton blooms.

Weekly composite of Chl. *a* imagery showed patches with high concentrations ($>0.5 \text{ mg m}^{-3}$) over the entire study area (Fig. 10). The in situ observation also showed more or less similar concentration in the upper 20 m ($>0.22 \text{ mg m}^{-3}$) irrespective of transects. In general, phytoplankton community in an enriched condition is usually dominated by diatoms. Madhu et al. 2006 reported the dominance of diatoms (91 to 95.4 %) from

the SWBoB, mainly pennate diatoms like *Thalassionema nitzschioids*, *Skeletonema costatum*, *Coscinodiscus* spp., *Thalassiothrix longissima*, *Nitzschia seriata*, *Chaetoceros* spp. and *Rhizosolenia* spp. In our study, a slightly lower concentration along the 13° N transect could be attributed to the grazing by higher level organisms which was abundant along this transect. The peripheral regions (11° N and 15° N) sustained comparatively higher concentration than the core of the eddy (13° N). This high concentration at the

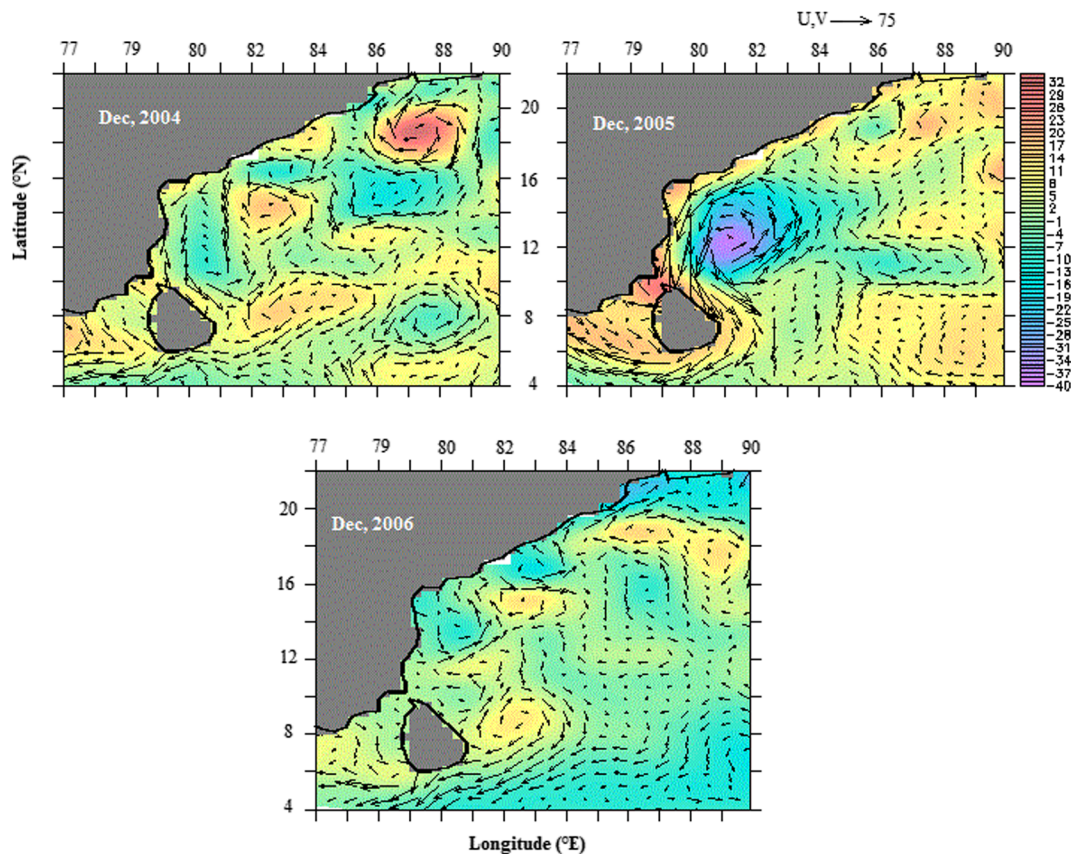


Fig. 7 Inter-annual variability of the SSHA (cm) and geostrophic currents (cm/s) in the BoB from 2004 to 2006

periphery could be attributed to the frontal characteristics of the edges that support high phytoplankton standing stock as suggested by Franks (1992). A study by Vinayachandran and Mathew (2003) has reported the blooming of phytoplankton in the southern BoB during winter as a result of cyclonic gyre. Although winter blooming is an annual feature in the southern BoB, the extent, duration and Chl. *a* concentration may vary from year to year. In a similar event of super cyclone during October 1999 sustained high primary production (Madhu et al. 2002). The frequent cyclonic storms, depression and deep depressions in the study region ensure the persistent Ekman transport which ultimately results in the phytoplankton bloom. Such enhancement in the Chl. *a* concentration as noticed in the present study was due to the combined effect of cyclonic storms and deep depressions along with the CE in the SWBoB.

The response of secondary standing stock (both micro and meso) to CE was also evident in the present study. Microzooplankton (20–200 μm) abundance in the upper 120 m varied between 9×10^4 and 16×10^4

ind. m^{-2} at 11°N and 13°N , respectively (Fig. 11). The microzooplankton community was dominated by 73 % of ciliates (CTS) along 11°N , whereas heterotrophic dinoflagellates (HDF) were dominant (37 and 53 %) along 13° and 15°N , respectively. Ciliates contributed only 4 % along both these transects. The higher number of ciliates at 11°N might be due to the patch of preferable fraction of phytoplankton cells. Studies in marine systems indicate that the abundance of CTS is related with the availability of smaller phytoplankton (Godhantaraman and Krishnamurthy 1997; Heinbokel and Beers 1979). The cell size of phytoplankton is assumed to be linked with the physical state of the system, and in the present observation, it might be linked to the age of the eddy.

However, the total abundance of microzooplankton during the present study was markedly lower than earlier reports from the same area during the winter monsoon (Jyothibabu et al. 2008). This lower abundance can be attributed to two conditions; firstly, the relative colder surface waters during the winter monsoon compared to

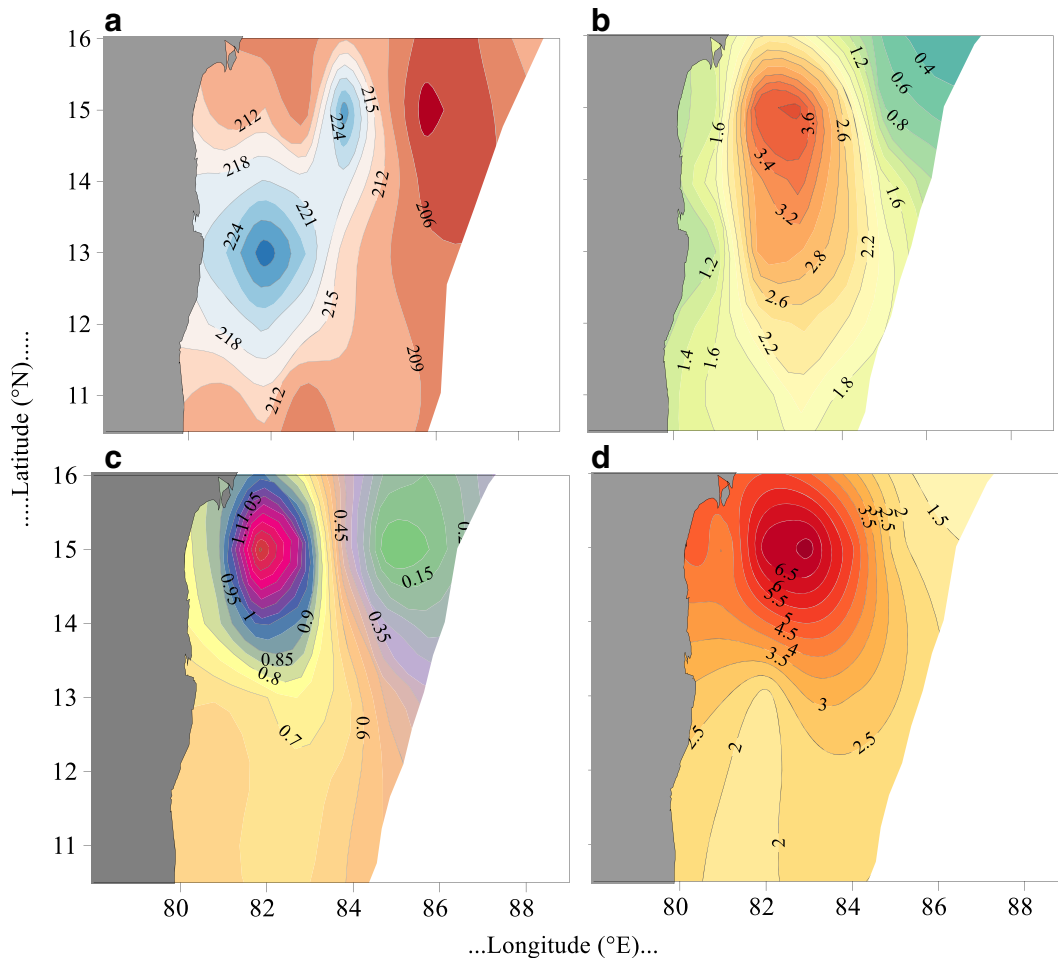


Fig. 8 Distribution of **a** dissolved oxygen (μM), **b** nitrate (μM), **c** phosphate (μM) and **d** silicate (μM) in the Bay of Bengal during winter monsoon

other seasons might have caused low abundance (Jyothibabu et al. 2008); and secondly, the nutrient enriched condition of the CE might have favoured dominance of large-sized phytoplankton cells (Cushing 1989). Hence, the low abundance of total microzooplankton in the study region suggests the prevalence of short food chain rather than microzooplankton-mediated food web in such gyre ecosystems.

Variations in mesozooplankton ($200\ \mu\text{m} - 20\ \text{mm}$) biovolume, abundance and community structure were prominent in the CE. In the mixed layer, the mesozooplankton biovolume ranged between 0.35 and $1.4\ \text{ml m}^{-3}$ (Fig. 12) with an average of $0.85\ \text{ml m}^{-3}$. High biovolume ($1.4\ \text{ml m}^{-3}$) in the mixed layer was observed at two locations ($15^\circ\ \text{N}, 81^\circ\ \text{E}$ and $13^\circ\ \text{N}, 82^\circ\ \text{E}$) of which $13^\circ\ \text{N}, 82^\circ\ \text{E}$ corresponds to the core region

of the CE. In the thermocline layer², the biovolume ranged from 0.08 to $0.69\ \text{ml m}^{-3}$ with the maximum at $13^\circ\ \text{N}, 81^\circ\ \text{E}$. In the deeper strata viz., below the thermocline to $300, 300-500$ and $500-1000\ \text{m}$, the values recorded were $<0.13\ \text{ml m}^{-3}$ (Fig. 13), except in a few locations attributed to swarming events of *Pyrosoma*. The increase in the mesozooplankton biovolume in response to the CE during the observation time was comparable to those reported by Sabu et al. 2015 from the cyclonic eddy region, whereas it was somewhat higher than that of Jyothibabu et al. 2008 ($777\ \text{mg Cm}^{-2}$; back calculated as $\sim 3.5\ \text{ml m}^{-2}$) from the western BoB during winter monsoon. Since the studies pertaining to the zooplankton during the winter monsoon were few, comparisons were made with the sum-

² Thermocline layer varied from 129 to 188 m in the study region.

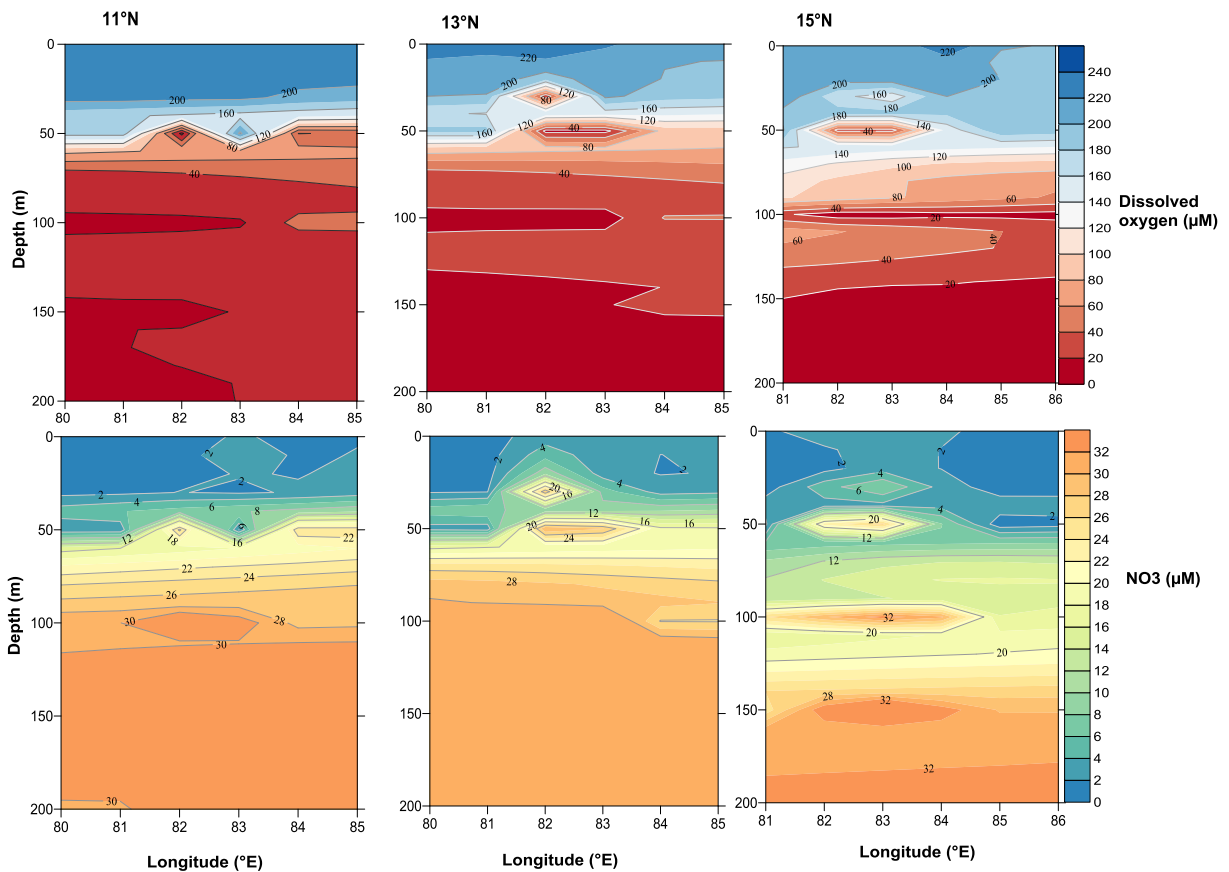


Fig. 9 Vertical profiles of dissolved oxygen (μM), nitrate (μM), silicate (μM) and phosphate (μM) along 11°N , 13°N and 15°N transects during the study period

mer monsoon reports in order to understand its differential response to CE (Nair et al. 1981; Muraleedharan et al. 2007; Fernandes and Ramaiah 2009). It is found that the biovolume recorded in the SWBoB during winter monsoon 2005 was higher or sometimes comparable to the above reports (Table 1). Fernandes and Ramaiah 2014 has observed high biomass from the SWBoB during the same period and suggested upwelling like processes in the area. However, the higher biomass observed in the present study from the same region may be associated with the existence of a large cyclonic eddy which is evident from the close resolution sampling ($1^\circ \times 1^\circ$). Events such as CE enhance the biological production of the bay which is at times comparable to its western counterpart, Arabian Sea (Madhupratap et al. 1996), during winter monsoon.

Consistent to the biovolume, numerical abundance of mesozooplankton ranged between 70 and 4288 ind. m^{-3} and was considerably higher in the mixed layer. At the core region of CE, the mesozooplankton abundance

recorded was $>800 \text{ ind. m}^{-3}$ (13°N ; 82°E) which was comparably higher than the other stations along 13°N (Table 2). In general, mesozooplankton abundance was noticeably higher in the study region, and it can be attributed to the availability of rich phytoplankton standing stock for effective grazing. Patch of higher abundance (4288 ind. m^{-3}) observed at 11°N , 83°E , which was many times higher than other stations, was contributed by 93 % (Fig. 14) of copepods (4000 ind. m^{-3}). This higher abundant patch of copepods without corresponding increase in biovolume is due to the contribution by small-sized individuals. This can be attributed to the availability of high phytoplankton for grazing and also the occurrence of ciliates in the microzooplankton community at the same region, which is considered to be the preferred food of copepods (Calbet and Saiz 2005). However, in the thermocline layer, the mesozooplankton abundance was relatively low and varied from 4 to 498 ind. m^{-3} . Along 13°N , thermocline layer supported relatively lower abundance of

mesozooplankton than 11 and 15° N. In the deeper depth strata, the abundance was <math><100 \text{ ind.m}^{-3}</math>. The total abundance of mesozooplankton showed significant variation ($p<0.05$) between different depth strata which may be due to the low stock of phytoplankton towards deeper depths.

The mesozooplankton abundance in the core region (13° N; 82° E) of the CE sustained relatively higher mesozooplankton abundance ($>800 \text{ ind.m}^{-3}$) in the mixed layer with 93 % of copepods followed by 1.46 % chaetognaths (Fig. 14). However, in the thermocline layer, the abundance observed was very low, 19 ind.m^{-3} , of which 66 % of the total was contributed by copepods followed by euphausiids (9 %) and chaetognaths (7 %). Higher abundance in the mixed layer and lower abundance in the thermocline layer in the core region can be attributed primarily to availability of nutrients and the resultant proliferation of phytoplankton in the mixed layer, which might have attracted zooplankton community chiefly for feeding purpose. In the water column above the thermocline layer, the biological activity goes on rapid rate (Banse 1964) and physically homogenous water column provide more congenial environment for zooplankton (Nair et al. 1977). In the present study, the upper column (mixed layer) of the eddy core region was highly active in order to support the zooplankton community compared to the thermocline layer.

Also at the locations other than the core of the CE, the community was dominated by copepods, followed by chaetognaths and appendicularians both in the mixed layer and the thermocline layer. Relative contribution of copepods ranged from 71 to 96 % in the mixed layer and 78 to 95 % in the thermocline layer. The contribution of chaetognaths and appendicularians in the mixed layer ranged from 1.4 to 10 % and <math><1</math> to 19 %, respectively. Along 15° N transect, locations with <math><80\%</math> copepods were found to harbour a greater number of appendicularians (-11 %) followed by chaetognaths (-7 %). Similarly along 13 and 11° N transects, chaetognaths and appendicularians occupied the second and third ranks in the mesozooplankton community. The presence of carnivorous groups, like chaetognaths, suggests a high predation pressure on copepods, and the omnivorous group, like appendicularians (chiefly detritivory), was supported by the availability of dissolved organic matter either through the disposal of fine detrital/faecal matters or other decomposed organic material. Dominance of

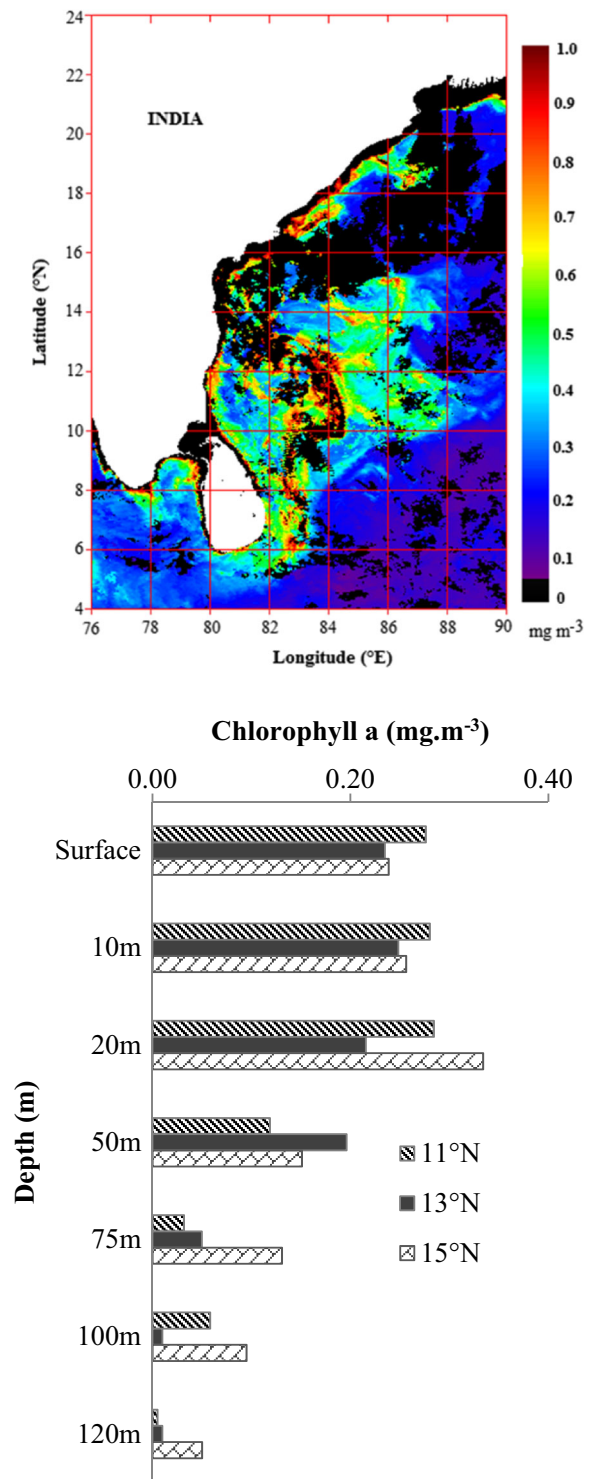


Fig. 10 a Weekly composite of satellite-derived chlorophyll a concentration during the last week of December 2005 (black colour in the map showing missing data regions); b vertical profile of Chl. a (mg m^{-3}) at 11° N, 13° N and 15° N in the western Bay of Bengal

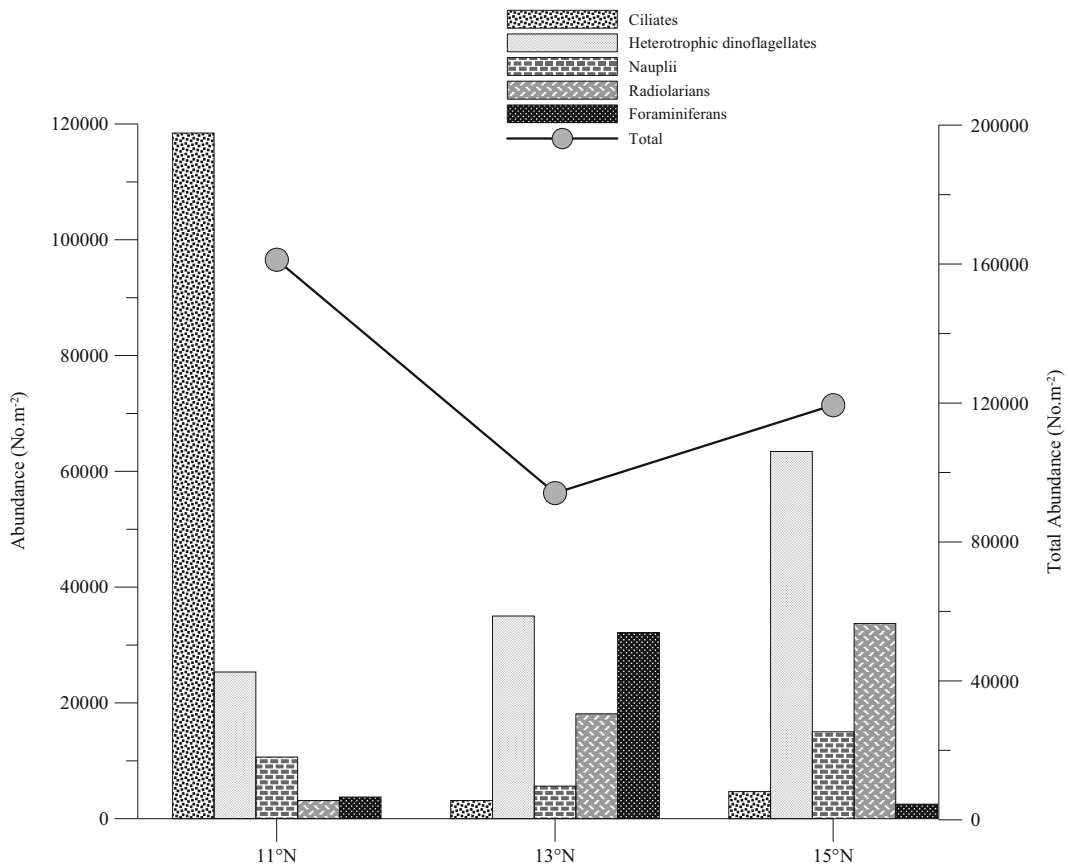


Fig. 11 Latitudinal variation in the percentage contribution of CTS (Ciliates), HDF (Heterotrophic dinoflagellates), NAUP (Nauplii), RADL (Radiolarians) and FORMS (Foraminifera) to the microzooplankton community in the Bay of Bengal during winter monsoon 2005

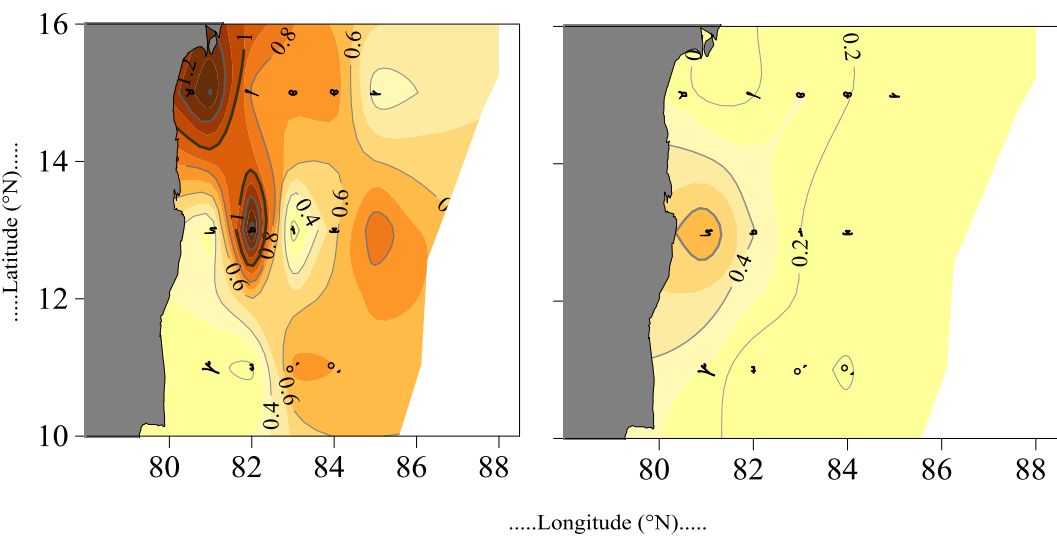


Fig. 12 Mesozooplankton biovolume (ml m⁻³) in the mixed layer and thermocline layer during winter monsoon 2005

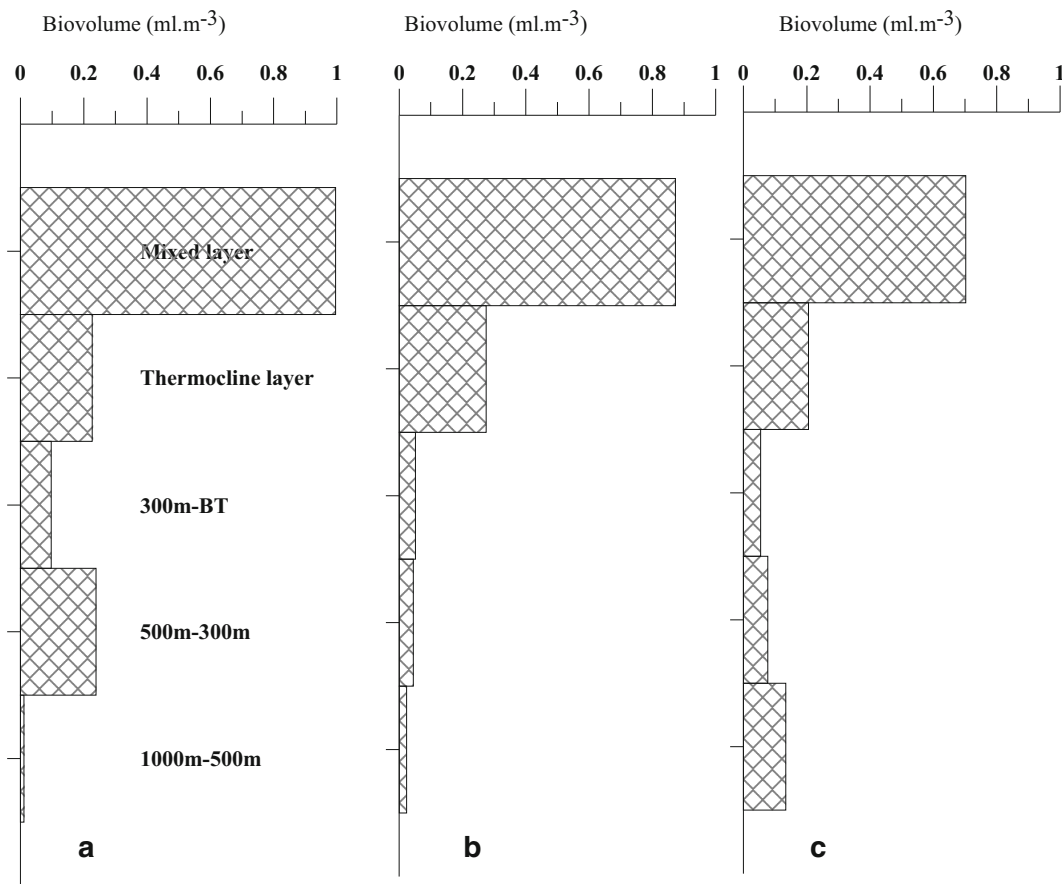


Fig. 13 Distribution of mean mesozooplankton biovolume in the upper 1000 m along **a** 15° N, **b** 13° N and **c** 11° N transect

active grazers like copepods, carnivorous groups, like chaetognaths, and detritivorous, like appendicularians, in the study region denotes the prevalence of short classical food chain and supports the enhanced vertical

transport of organic carbon from the surface to deep waters.

Variations in the zooplankton distribution pattern in the mesoscale eddies depends on many factors like

Table 1 Comparison of mesozooplankton biomass with previous studies

Sl. No.	Area	Season	Sampling layer	Zooplankton biomass (mg Cm ⁻³)	Reference
1	Western Bay of Bengal	Summer monsoon		0.2 to 21.9	Nair et al. 1981
2	Northeastern Arabian Sea	Winter monsoon	Mixed layer	14.6	Madhupratap et al. 1996
3	Western Bay of Bengal	Winter monsoon	Surface to bottom of thermocline	777 mg Cm ⁻²	Jyothibabu et al. 2008
4	Western Bay of Bengal	Summer Monsoon	Mixed layer	3–31	Fernandes and Ramaiah 2009
5	Central Bay of Bengal	Summer monsoon	Mixed layer	9–104	Fernandes and Ramaiah 2009
6	Southern Bay of Bengal	Summer monsoon	Mixed layer	2.43	Vidya et al. 2013
7	Western and central Bay of Bengal	Winter monsoon	Surface	12.4 to 159.8	Fernandes and Ramaiah 2014
8	Southwestern Bay of Bengal	Winter monsoon	Mixed layer	144	Present study

Units for Sl. No. 3 is represented in m⁻²

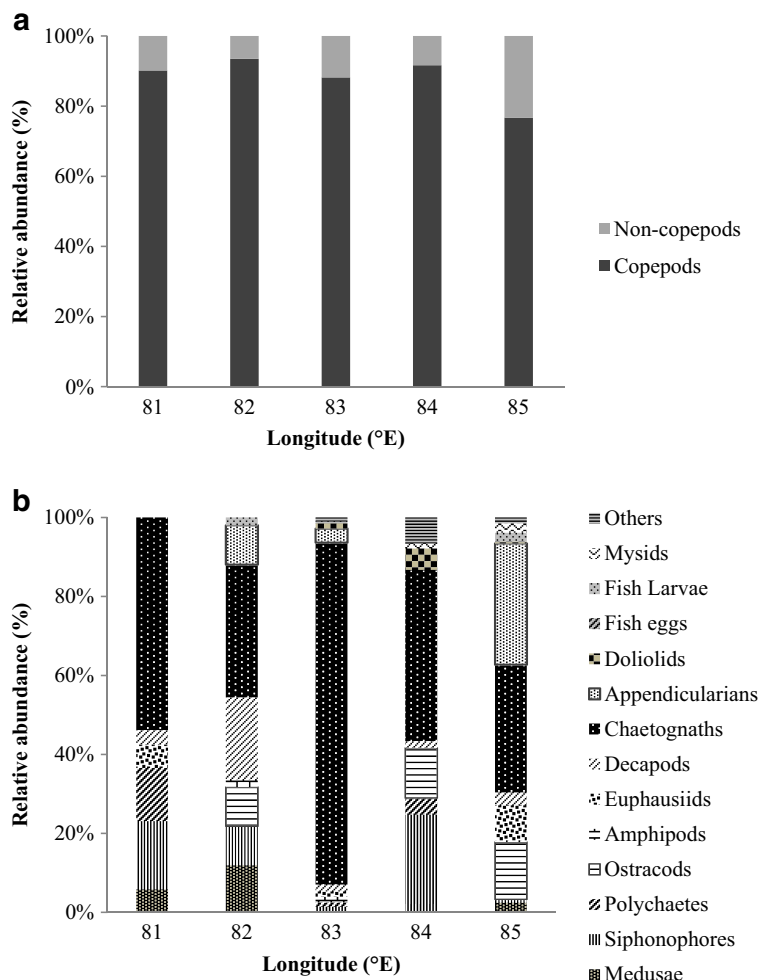
Table 2 Station wise abundance of mesozooplankton (ind.m⁻³) in the southern Bay of Bengal during winter monsoon 2005

Latitude (°N)	Longitude (°E)	Mesozooplankton abundance (ind.m ⁻³) in different depth strata				
		Mixed layer	Thermocline	BT-300	300–500	500–1000
11	82	582	120	23	20	25
	83	4288	428	47	15	10
	84	582	498	41	10	3
	85	646	26	78	4	12
13	81	70	128	37	7	1
	82	843	19	21	11	10
	83	321	17	7	9	3
	84	283	4	33	6	38
	85	271	88	42	19	13
15	81	752	145	12	11	3
	82	591	169	37	100	2
	83	566	316	33	12	1
	84	989	203	38	11	8
	85	284	167	20	1	7
	86	345	55	44	9	6

source water, age, size, intensity, forcing mechanisms, interaction with wind events etc. (Owen 1981; Benitez-Nelson and McGillicuddy 2008; Morales et al. 2010). In our study, the variations of chl. *a* and zooplankton biovolume, abundance and composition between the core and non-core regions of eddy can be influenced by the age, size, intensity, interaction of eddy with wind events as well as the propagation of the eddy. The eddy with strong cyclonic circulation was evolved in the area during November 2005 and subsequent wind events such as cyclonic storms, deep depression and depression intensified the CE. Thus, the large area was influenced by this 3- to 4-week-old CE and associated circulation which resulted in an enhancement in the phytoplankton standing stock of the area. The eastward propagation of core of the CE was also evident in the satellite imagery. Hence, the higher biovolume and abundance of mesozooplankton in the core region suggest the retention of zooplankton community in the core. Also, the high grazing activity of the retained mesozooplankton in the core resulted in relatively low in situ Chl. *a* in the upper column. Studies based on the cold core rings observed in the Gulf Stream also recorded higher primary production in the core region through the entrainment of surrounding water masses in the ring (Kennelly et al. 1985; Hitchcock et al. 1993; Arístegui et al. 1997; Leterme and Pingree 2008).

The alterations in the primary and secondary levels (due to changes in the environment, resulting from the episodic events such as eddies and gyres in oligotrophic region like BoB) are influential in determining the production at tertiary level. We considered the trends in oceanic tuna resources to relate the implications at tertiary level as several studies have documented that this resource is closely related to events like El Nino, La Nina (Satheesh Kumar et al. 2014) and Indian Ocean dipole events (Lan et al. 2012). In the Indian waters, oceanic tuna are represented by three species dominated by yellowfin tuna (94.6 %), dogtooth tuna (1.5 %) and big-eye tuna (3.9 %) (Abdussamad et al. 2012). Published results from National Fishery Data Collected by Central Marine Fisheries Research Institute (CMFRI) suggested that yellowfin tuna resources were remarkably higher along the southeast coast than northeast, northwest and southwest coasts. An increase in the tuna fishery along the southeast coast was observed during the years 2006 and 2007 (Abdussamad et al. 2012), which was subsequent to our observation period. To some extent, the increase in fishery resources during the subsequent years (2006 and 2007) of our observation (2005) can be attributed to such atmospheric and oceanic events such as cyclones and eddies as observed in the present study. Further in situ oceanographic observations integrated with fish landing information

Fig. 14 Relative abundance (%) of **a** copepods and non-copepods and **b** various non-copepod taxa in the mixed layer along 13° N transect (others comprised of minor groups like foraminiferans, pteropods, heteropods, bivalves, salps, gastropods, cephalopods, stomatopods and amphioxus)



would provide better understanding on the influence of episodic events such as eddies and cyclones in the BoB on tertiary level production.

Conclusion

Physical processes such as cyclonic eddies during winter monsoon show strong inter-annual variations in the intensity. During winter 2005, cyclonic eddy circulation was prominent in the SWBoB, which significantly influenced the biological production. In addition, atmospheric disturbances such as depressions, deep depressions, cyclones etc. experienced during the period, maintained the strength of the cyclonic eddy. High turbulence due to the combined effect of frequent cyclonic storms and strong and large-scale cyclonic

circulation delivered appreciable quantity of nutrients to the photic zone, leading to the development of the food web dominated with larger cells that transfer a greater proportion of primary productivity to higher trophic level (Legendre 1981; Michaels and Silver 1988; Legendre and Gosselin 1989; Kiørboe 1993). The zooplankton community structure during the present study also showed the prevalence of short traditional food chain in the region. The observed values of Chl. *a* and mesozooplankton biovolume was comparable to the productive region of the northern Indian Ocean, i.e. northeastern Arabian Sea during the winter monsoon. In the present study, high biological production, both at primary as well as secondary level suggests the prevalence of an efficient food web as a result of physical forcing and subsequent ecological interactions evident up to tertiary level in an oligotrophic basin, like BoB.

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