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Role of Cyclonic Eddy in enhancing Primary and New production in the Bay of Bengal

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Abstract

Eddies can be important in sustaining primary production in the tropical oceans, but their role for nutrient cycling is poorly understood in the under-sampled northern Indian Ocean. To assess the role of cyclonic eddies in enhancing primary production, measurements of primary production were carried out at four stations in the northern Bay of Bengal during the early winter 2007, around a cyclonic eddy close to 17.8 °N, 87.5 °E. Shallowing of the thermocline and halocline by 10 m was observed within the eddy compared to the surroundings; mixed layer depth was also reduced within the eddy. The highest surface productivity (2.71 μM C d^{-1}) and chlorophyll *a* (0.18 μg L^{-1}) were found within the eddy, while the lowest, at its outer edge. Further, the eddy supplied nutrients to the surface layers, shallowing the subsurface chlorophyll maximum as well. Integrated production in the euphotic top layers was more than twice within eddy compared to its outer edge, confirming the role of cyclonic eddies in enhancing the primary production in the otherwise less productive Bay of Bengal. Given new nitrogen input via vertical mixing, river discharge or aerosol deposition, the additional primary production due to this new nutrient input and its contribution to the total production (*f*-ratio, fraction of exportable organic matter) increased significantly from 0.4 to 0.7, and thus the Bay of Bengal can potentially transfer a high fraction of its total production to the deep, assisted by eddies. We suggest possible improvements in experiments for future studies, and the potential for assessing the role of eddies in biogeochemistry.

Key words: Chlorophyll, cyclonic eddy, *f*-ratio, nutricline, new production, river discharge

1. Introduction

The Bay of Bengal - in the eastern part of the northern Indian Ocean, is landlocked in the north and forced by seasonally reversing monsoonal winds (Schott and McCreary, 2001). The biogeochemistry of the Bay of Bengal is governed by these monsoonal winds and associated circulation patterns (e.g., Prasanna Kumar et al., 2010a). The excess of precipitation (an annual average of ~2 m; Gill 1982) over evaporation, together with large freshwater influxes from the subcontinent rivers (~1.5×10^{12} m^3 y^{-1}; UNESCO, 1988), lower the surface salinity and also generate stable stratification in the euphotic layers of the northern Bay of Bengal (Prasad, 1997). This riverwater influx into the Bay maintains a ~25 m thick barrier layer (a layer between the base of mixed layer and the top of the thermocline) that prevents the upward supply of nutrients and limits primary production throughout the late summer and post-monsoon (Vinayachandran et al., 2002). During this period, heavy cloud cover and sediment load minimize solar irradiance, which limits primary production. Therefore, the Bay of Bengal is generally viewed to be less productive (typically 250 mg C m^{-2} d^{-1}) than its western counterpart, i.e. the Arabian Sea (typically 1 g C m^{-2} d^{-1}, e.g., Kumar et al., 2004; Jyothibabu et al., 2004; Singh et al., 2012). Although the upper layers of the Bay of Bengal are stratified, eddy pumping has been suggested as a possible mechanism for transferring nutrients into the euphotic zone and increasing primary production (Gomes et al., 2000; Prasanna Kumar et al., 2004).

Oceanic eddies are circulating water masses that are either cyclonic (colder water and lower sea level at the center) or anticyclonic (warmer water and elevated sea level at the center) (Falkowski et al., 1991). Cold-core eddies are important because they cause an upward displacement of the nutricline along isopycnals and inject nutrients to the surface (Falkowski et al., 1991), thus potentially enhance primary production and downward carbon export downward in the Bay of Bengal (Ramasastry and Balaramamurty, 1957; Shetye et al., 1993; Prasanna Kumar et al., 2007). Prasanna Kumar et al. (2007) observed an increase in surface nitrate (NO_3^-) and silicate (H_4SiO_4) in the Bay of Bengal through eddies during both fall and spring followed by higher concentrations of chlorophyll; also eddy-pumping reduced the depth of the subsurface chlorophyll maximum. Response of biological activity to cyclonic eddies was low during the summer 2003 in the northern Bay, although the Bay was highly eutrophic (Muraleedharan et al., 2007). But, more importantly, Muraleedharan et al., (2007) inferred that primary production switched from ‘regenerated’ to ‘new’ production without supporting data on new production. While there have been some studies pertaining to the role of eddies in primary production in the Bay of Bengal (Madhupratap et al., 2003, Prasanna Kumar et al., 2002; 2004), no such research has been conducted its effect on new production. We have measured for the first time new and primary production using ^{13}C and ^{15}N tracers in and around an eddy identified in the northern Bay of Bengal. Our aim was to understand the dynamics of new and total primary production in and around the cyclonic eddy in the northern Bay of Bengal.

2. Materials and Methods

2.1. Sampling and experimental strategy

A rosette sampler equipped with Niskin bottles was operated along two transects within a 3° × 3° box – Latitude 16-19 °N and Longitude 86-89 °E – and along its perimeter from 25 November to 14 December 2007 in the northeastern Bay of Bengal (Fig. 1). Vertical profiles of temperature and salinity for the sampling locations were obtained using the CTD (SBE 911 Plus, Seabird Electronics Sea, USA). The mixed layer depth was defined as the depth at which the vertical gradient of potential density (σ_θ) was exceeded by 0.05 kg m^{-4} (Vinayachandran et al., 2002).

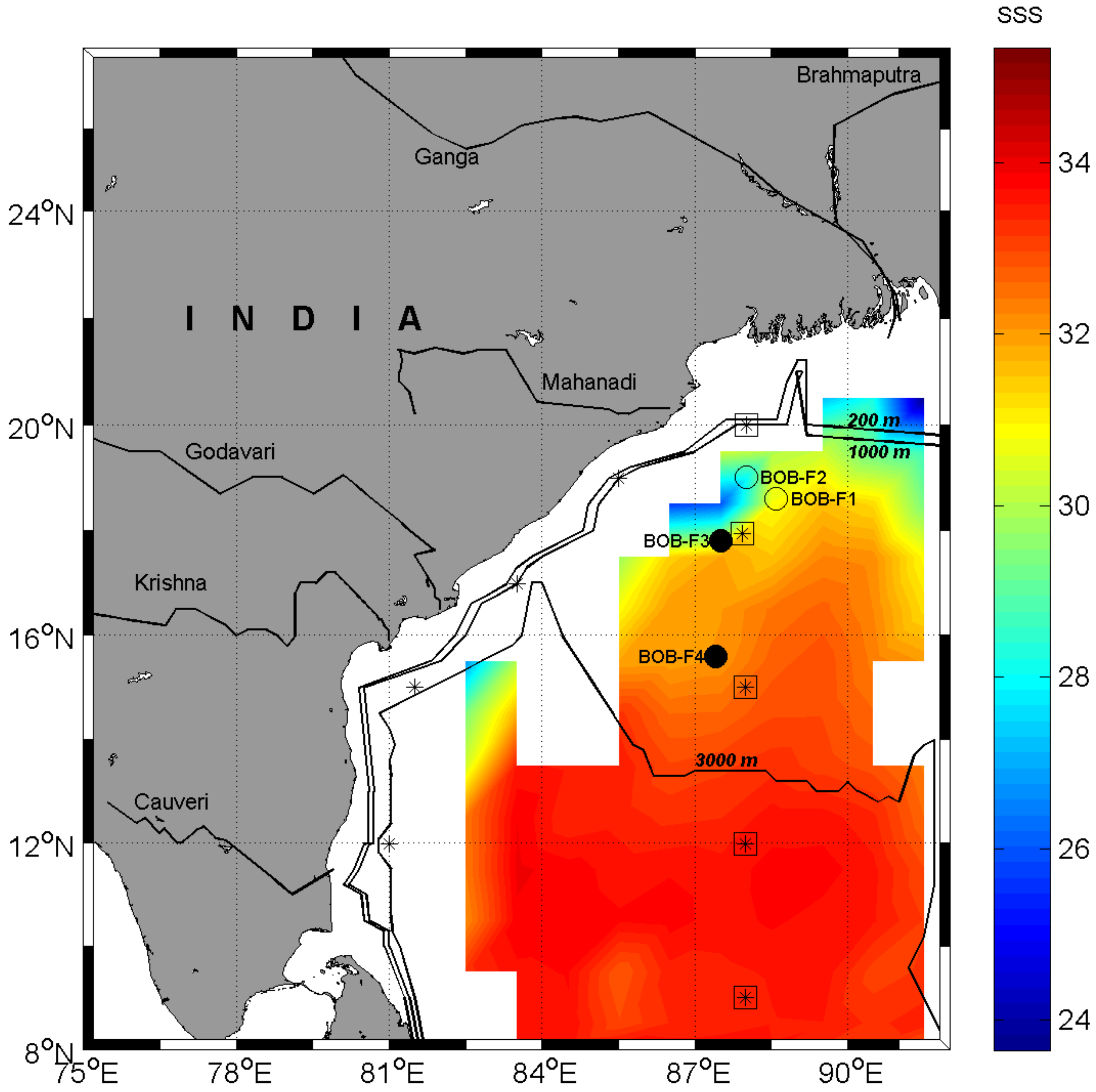

Figure 1. Sea surface salinity (SSS) during November 2012 from the Aquarius data (available at http://data.nodc.noaa.gov/las/getUI.do) with superimposed sampling locations. C uptake rates measurements were carried at BOB-F1, BOB-F2, BOB-F3 and BOB-F4, as shown in (filled and unfilled) circles. N uptake rates measurements were carried out at BOB-F3 and BOB-F4, as shown in unfilled circles. Sampling locations for Madhupratap et al. (2003), Prasanna Kumar et al. (2004; 2007), Kumar et al. (2004) are shown in asterisk symbols, while that of Prasanna Kumar et al. (2002) are shown by square symbols. Contours are ocean depth (m).

Joint Global Ocean Flux Study (JGOFS) protocol (UNESCO, 1994) was followed to estimate new and regenerated production. Six sampling depths were chosen to cover the euphotic zone with light intensity corresponding to 100, 80, 64, 20, 5 and 1% of the sea surface irradiance. A photosynthetically-active-radiation sensor (QSP–2300; Biosphericals, USA) attached to a portable CTD sensor system (SBE 19plus) was used to measure irradiance levels. Individual water samples were collected in pre-washed polycarbonate bottles (Nalgene, USA) for Carbon (1 L), NO_3^- (2 L), ammonium (NH_4^+; 2 L) and urea (1 L) enrichment experiments, each in duplicate. Samples were also collected at each station for blank corrections for all the tracers. Prior to incubation at 10:00 h local time, tracers containing 99 atom% ^{13}C ($NaH^{13}CO_3$, Cambridge Isotope Laboratories, Inc. USA) and ^{15}N ($Na^{15}NO_3$, $^{15}NH_4Cl$ and $^{15}NH_2$-CO-$^{15}NH_2$, Sigma-Aldrich, USA) were added to the bottles. A constant amount (~0.2 mmol L^{-1}) of $NaH^{13}CO_3$ was added to each bottle for C uptake measurements. NO_3^- ($Na^{15}NO_3$) tracer was added at less than 10% of the ambient concentration. Ambient NH_4^+ and urea could not be measured because of logistic reasons; a small, constant amounts of $^{15}NH_4Cl$ and $^{15}NH_2$-CO-$^{15}NH_2$ tracers were added (to a final concentration of 0.01 μmol L^{-1}), following Watts and Owens (1999). To simulate the irradiance at the depths from which samples derived, well-calibrated neutral density filters were put on the sample bottles. Subsequently sample bottles were kept in a big plastic tub and seawater from a depth of 6 m was circulated to regulate the temperature during on deck-incubation from 10:00 to 14:00 h at each station (UNESCO, 1994). Immediately after the incubation, samples were transferred to the shipboard laboratory for filtration and were kept wrapped in a thick black cloth and in the dark until the filtrations were over. All samples were filtered in the dark, sequentially through pre-combusted (4 h at 400 °C) 47 mm diameter and 0.7 µm pore size GF/F filters (Whatmann, GE Healthcare, USA). Samples were filtered under low vacuum (<70 mm Hg) using a manifold filtration unit and vacuum pump (Millipore, USA). Subsequently, filters were dried in an oven at 50 °C overnight and stored for further mass-spectrometric analyses. For blank correction, zero time enrichment was estimated: the same concentrations of isotopically enriched tracers as in the samples were added to the individual blank-samples. Immediately after the addition, these samples were likewise filtered and dried for isotopic analysis.

2.2. Nutrient and chlorophyll a measurements

One hundred ml of sea water sample was collected separately for nutrient measurements at each sampling location. Nutrients were measured using an autoanalyser (Skalar model 5100/1) following standard techniques (UNESCO, 1994). Detection limits for NO_3^-, phosphate (PO_4^{3-}), and H_4SiO_4 were 0.1 µmol L^{-1}, 0.01 µmol L^{-1}, and 0.1 µmol L^{-1}, respectively. Error in the nutrient measurements is less than 1% for the concentrations >1 µmol L^{-1}, while it reaches as high as 5% for low ambient values. For Chlorophyll *a* measurements, 1 L water from each depth was collected and filtered through 47 mm diameter and 0.7 µm pore size GF/F filters (Whatmann) under low vacuum. Chlorophyll *a* was then extracted using 10 ml of 90% acetone (AR grade) and was measured using a fluorometer (Turner Design, USA).

2.3. Calculations of new, regenerated and total production

Generally, the tracer used to measure oceanic primary productivity is ^{14}C, which provides an estimation of overall productivity, i.e., total rate of carbon uptake. However, this tracer does not provide any information about the export/new production. The ^{15}N tracer technique (Dugdale and Goering, 1967), besides estimating the primary productivity, yields the new/export productivity as well (i.e. nitrate uptake).

A CarloErba elemental analyzer interfaced via Conflo III to a Finnigan Delta Plus mass spectrometer was used to measure particulate organic nitrogen (and carbon) and atom% ^{15}N (and ^{13}C) in the filters. For nitrogen, calibrated in-house casein and international standards $(NH_4)_2SO_4$ (IAEA-N-2) and KNO_3 (IAEA-NO-3) were used for checking the external precision whereas calibrated in-house starch and international standard ANU sucrose were used for carbon. The external precisions of the measurements were consistently better than 0.5‰. The maximum differences in the duplicate mass-spectrometric measurements of particulate organic nitrogen and carbon were found to be less than 10%. The coefficients of variation in atom% ^{15}N and atom% ^{13}C measurement were less than 1% (see Gandhi et al., 2010; 2011a for more details).

The equations of Dugdale and Wilkerson (1986) was used to calculate nitrogen uptake rate and the procedure of Slawyk et al. (1977) was used to estimate carbon uptake rates. The total N-uptake rate is the sum of NO_3^-, NH_4^+ and urea uptake rates. Euphotic-depth-integrated uptake rates were calculated by the trapezoidal method of integration. New productivity was considered equivalent to NO_3^- uptake rate and regenerated productivity, to the sum of NH_4^+ and urea uptake rates.

f-ratio (Eppley and Peterson, 1979) is the ratio of new production to total production (e.g., Sambrotto, 2001). The *f*-ratio calculated using nitrogen isotope uptake experiments assumes that nitrate is supplied by winter mixing or upwelling and none is generated within the euphotic zone (Fernandez and Raimbault, 2007). It is now recognized that substantial amount of nitrification may occur in the euphotic zone (Raimbault et al., 1999) with nitrogen fixation accounting for a significant fraction of new production in some regions (Karl et al., 1997;

Gandhi et al., 2011b; Singh et al., 2013), which may affect calculation of *f* ratio. Thus, for more realistic *f*-ratios, we have calculated total (labeled + unlabelled) uptake rates of NH_4^+ and urea by assuming their ambient concentrations to be ~0.1 μmol L^{-1} (Gandhi et al., 2011b). Generally, NH_4^+ concentrations are low in low-biomass and well-oxygenated waters (e.g., Lam et al., 2011). During the study period, the surface water was well oxygenated (dissolved oxygen >3 ml L^{-1} in the upper 100 m; Laongmanee et al., 2008) and less productive compared to other regions (see Results) so we assumed this concentration for NH_4^+. Further, data on ambient NH_4^+ and urea concentration have not yet been reported for this region; therefore, we assumed similar concentrations of NH_4^+ and urea. This provides lower bounds for the *f*-ratios. Daily uptake rates were calculated by multiplying hourly values by 12 for NO_3^-, urea and carbon and by 18 for NH_4^+ (Slawyk et al., 1977; Dugdale and Wilkerson, 1986; Dugdale et al., 1992).

3. Results

3.1. Hydrographic parameters

Table 1: Hydrographic parameters at different sampling locations in the Bay of Bengal.

Date	Station code	Lat (°N)	Lon (°E)	SST[a] (°C)	Salinity[b]	σ_θ (kg m^{-3})[c]	MLD (m)[d]	NO_3^- (mmol m^{-2})[e]	H_4SiO_4 (mmol m^{-2})[e]	PO_4^{3-} (mmol m^{-2})[e]	Chl *a* (mg m^{-2})[e]
29 Nov 07	BOB–F1	18.6	88.6	28.0	33.10	21.04	48	305	268	30	8
4 Dec 07	BOB–F2	19.0	88.0	27.5	33.08	21.15	19	382	246	28	11
8 Dec 07	BOB–F3	17.8	87.5	27.0	33.43	21.41	41	250	275	40	10
11 Dec 07	BOB–F4	15.6	87.4	27.5	33.48	21.39	49	75	157	32	8

[a]SST - Sea Surface Temperature, [b]Salinity, [c]σ_θ are at the surface; [d]MLD - Mixed layer depth, [e]Nutrients and chlorophyll *a* value are euphotic zone (50 m) integrated.

Euphotic zone was uniform (~50 m) at all the locations (BOB-F1-4). We followed standard criteria (thermohaline structure and sea surface height anomaly) to characterize eddies (Nuncio and Prasanna Kumar, 2012). Thermohaline structure along a transect, presented in Fig. 2D, showed oscillations with upward displacement of isotherms towards 87.5 °E. This structure confirms the presence of a cyclonic eddy close to 17.8 °N, 87.5 °E, which could be further verified by sea surface height anomaly data (Fig. 2D). Consequently, sampling locations BOB-F3 and BOB-F4 were respectively located within and at the outer edge of the eddy, respectively (Fig. 2 D, E and Fig. 3). Sea surface temperature varied between 27 and 28 °C (Table 1) and a difference of 0.5 °C was observed between locations BOB-F3 and BOB-F4. Sea surface temperature was higher at BOB-F1 and BOB-F2 (hereafter referred as northern locations), located relatively north and likely influenced by river discharge as sea surface salinity at these two stations are lower that that at the BOB-F3 and BOB-F4 (Fig. 1). Sea surface salinity changed from 33.08 to 33.48, regionally. No significant difference was observed in salinity between BOB-F3 (eddy location) and BOB-F4 (outer edge) (Table 1), however, salinity was significantly lower at the northern locations (Table 1). Figure 4 shows the profiles related to the CTD cast used for sampling waters for N and C uptake rate measurements. Both thermocline and halocline went up almost 10 m at the eddy location (BOB-F3) relative to the outer edge (BOB-F4) (Fig. 4C and 4D). A similar feature was observed in σ_θ profiles. Mixed layer depth also became shallower at BOB-F3 compared to BOB-F4 (Fig. 4C and 4D).

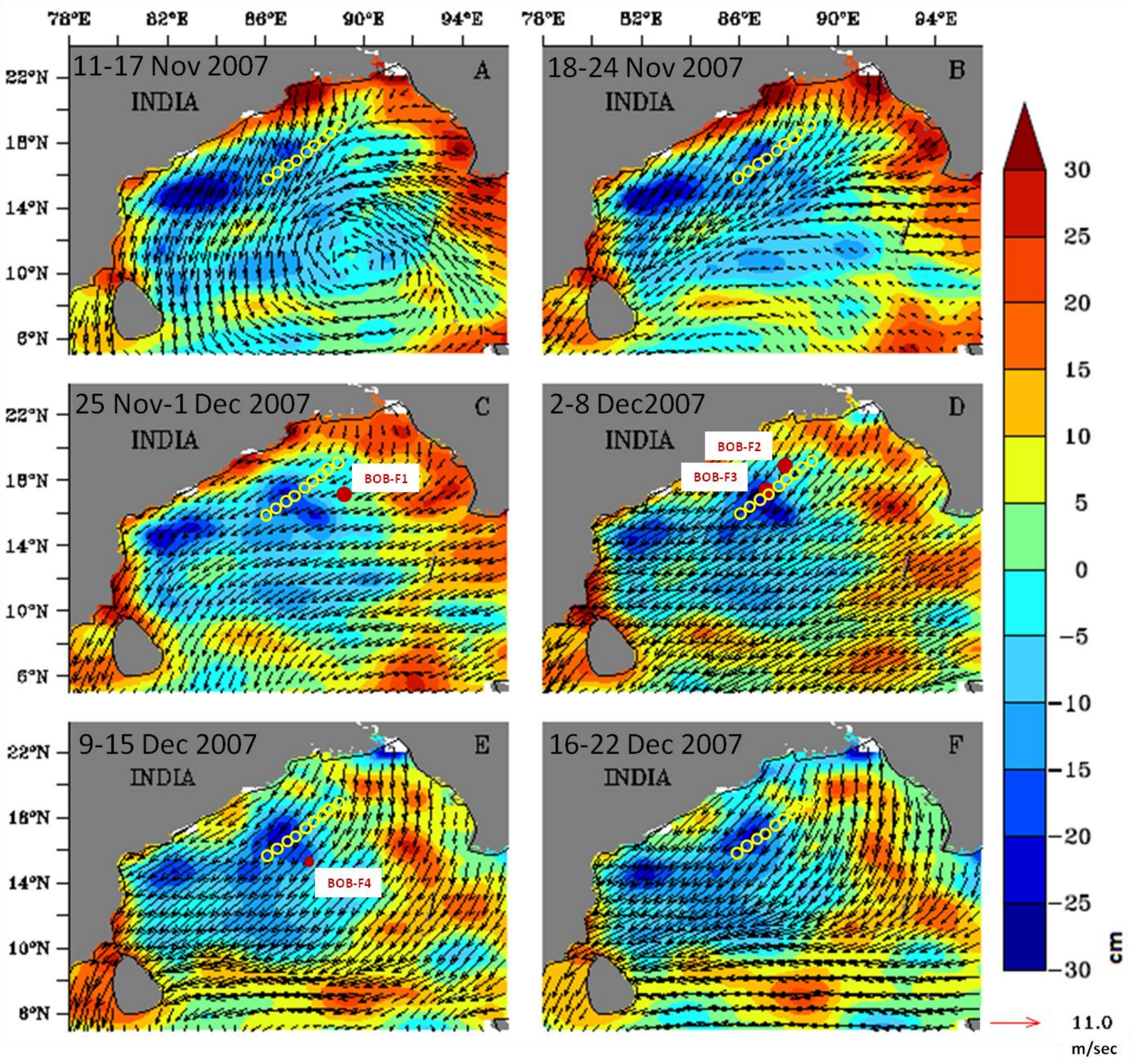

Figure 2. Sea surface height anomaly (in cm; source: http://iridl.ldeo.columbia.edu/SOURCES/.IGOSS/.TOPEX/.NOAA/.ssha/) images overlaid with surface winds (source: http://apdrc.soest.hawaii.edu/dods/public_data/satellite_product) showing different evolutionary stages (A-F) of the eddy (close to 17.8N, 87.5E) during A- 11-17 November, B-18-24 November, C- 25 November-1 December, D- 2-8 December, E- 9-15 December, F-16-22 December 2007 in the Bay of Bengal. CTD operation transect shown by yellow open circles and biological incubation stations are shown by red filled circles.

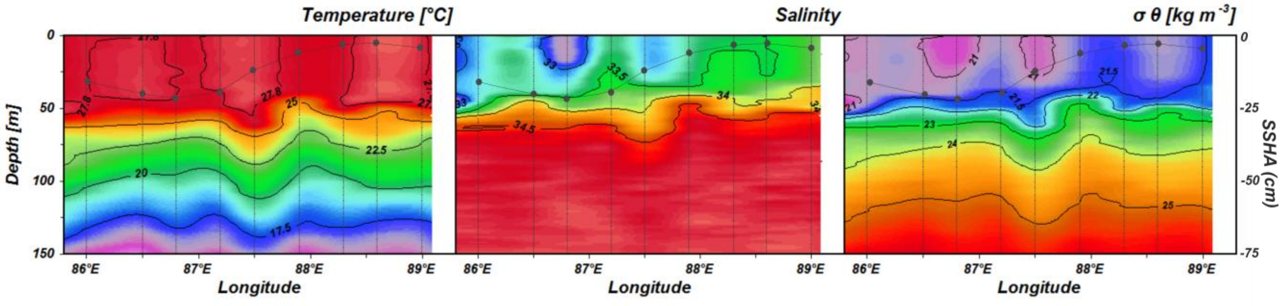

Figure 3. Vertical distribution of A- temperature (°C) B- salinity and C- σ_θ (kg m^{-3}) in the upper 200 m in the ocean along the transect shown in Fig. 2 D. CTD profiles are shown in vertical dotted lines.

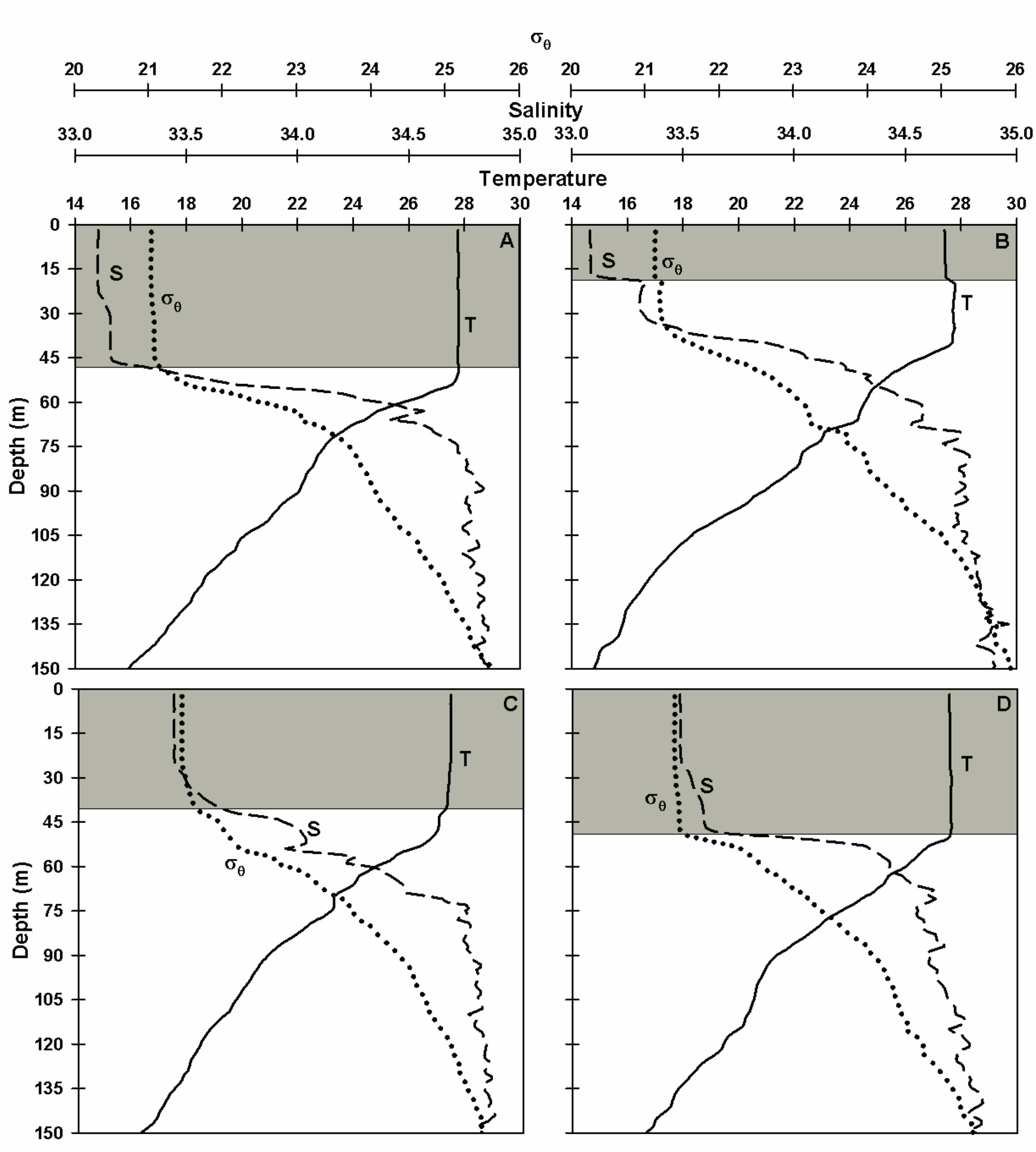

Figure 4. Depth profiles of temperature (°C), salinity and σ_θ (kg m^{-3}) at different sampling locations i.e. A- BOB-F1, B –BOB-F2, C –BOB-F3, D – BOB-F4.

3.2. Nutrients and chlorophyll

No difference was observed between BOB-F3 and BOB-F4 in terms of surface NO_3^- and PO_4^{3-}, although lower H_4SiO_4 values were observed at BOB-F4 (Fig. 5). Surface NO_3^- values at the northern locations were higher (>2 µmol L^{-1}) than those at the other two locations (~0.1 µmol L^{-1}). Surface PO_4^{3-} was higher at BOB-F3 and BOB-F4 relative to the northern locations (Fig. 5). Although no significant difference in surface NO_3^- was observed between BOB-F3 and BOB-F4, the euphotic-depth-integrated NO_3^- at BOB-F3 was about three times higher than that at BOB-F4 (Table 1). Likewise, integrated H_4SiO_4 and PO_4^{3-} were both higher at BOB-F3 than BOB-F4. Depth profiles of NO_3^- at BOB-F1, BOB-F2 and BOB-F3 did not show significant difference, but the nutricline became shallower at BOB-F3 relative to BOB-F4 (Fig. 5A). Unlike surface nutrients, surface chlorophyll *a* was highest (1.9 mg m^{-3}) at BOB-F3, twice that of BOB-F4 (Fig. 5D). Similarly, euphotic-depth-integrated chlorophyll *a* at BOB-F3 (>10 mg m^{-2}) was higher than BOB-F4 (Table 1). The subsurface chlorophyll maximum was close to the surface (within 10 m) at BOB-F3 and deepest (60 m) at BOB-F4 (Fig. 5D).

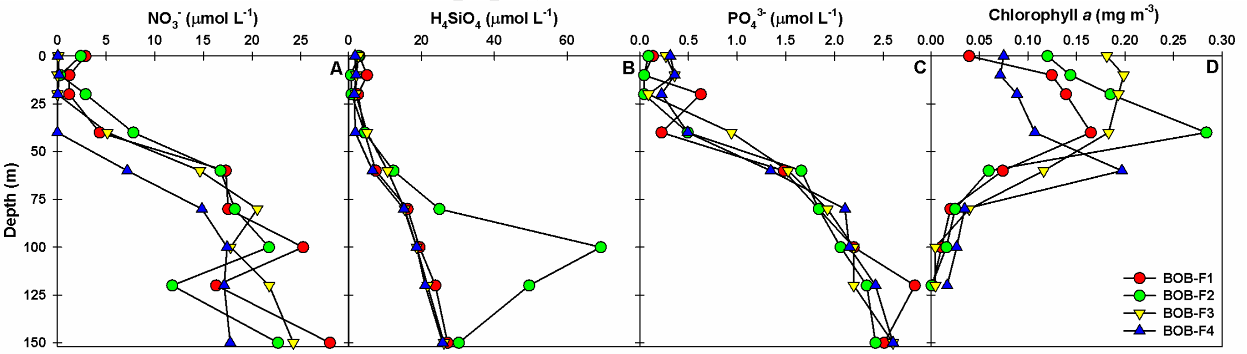

Figure 5. A- NO_3^-, B- H_4SiO_4, C- PO_4^{3-} and D- Chlorophyll a profiles at different sampling locations.

3.3. Carbon uptake rates

Surface productivity varied from 0.89 to 2.71 µmol C L^{-1} d^{-1} (1.53 ± 0.83 µmol C L^{-1} d^{-1}, mean ± standard deviation; Fig. 6A). The highest value was found at BOB-F3 while the lowest was at BOB-F4 (Fig. 6A). Except at BOB-F2, the highest C uptake was observed near the surface. C uptake was higher at BOB-F3 as compared to BOB-F4 at almost all the depths (Fig. 6A). Euphotic-depth-integrated carbon uptake rates varied from 16.9 to 35.8 mmol C m^{-2} d^{-1} (with an average of 25.9 ± 8.83 mmol C m^{-2} d^{-1}, Fig. 6B). At the eddy (BOB-F3), production was more than twice that at the outer edge of the eddy (BOB-F4).

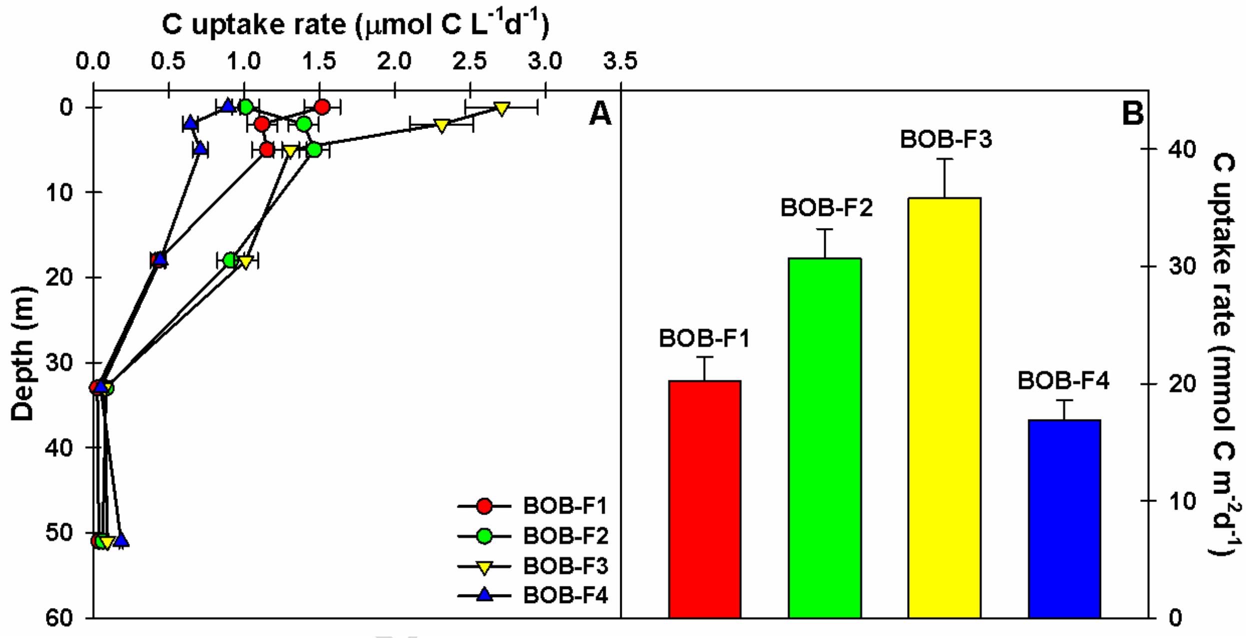

Figure 6. Depth profiles of C uptake rate and their B- euphotic-depth-integrated values at different locations in the Bay of Bengal. Errors associated with the values are 1-sigma standard deviation.

3.4. Nitrogen uptake rates and f-ratio

Surface NO_3^- uptake rate was lower at BOB-F3 compared to BOB-F4 (Fig. 7A), which was in contrast to the measured surface C uptake rate. Subsurface values of NO_3^- uptake were higher at BOB-F3 than BOB-F4. Euphotic-depth-integrated new production was more than twice at BOB-F3 compared to BOB-F4 (Table 2).

Table 2: N uptake rates and *f*-ratios at two sampling locations near the eddy

Station code	Lat	Long	N uptake rates (mmol N $m^{-2}d^{-1}$) ± $\sigma^{\dagger}$			*f*-ratio[#]
			$^{\times}\rho NO_3^-$	ρNH_4^+	ρUrea	
BOB–F3	17.8	87.5	69.5 ± 5.4	3.8 ± 0.2	1.4 ± 0.1	0.7
BOB–F4	15.6	87.4	24.2 ± 1.8	4.3 ± 0.4	1.0 ± 0.2	0.4

[†] σ is the standard deviation of primary and duplicate samples, [×] ρ stands for uptake rate, such as ρNO_3^- is uptake rate of nitrate, [#] *f*-ratio is calculated using estimated total (labelled + unlabelled) NH_4^+ and urea uptake rates. Total (labelled + unlabelled) NH_4^+ and urea uptake rates were estimated by assuming ambient concentrations of NH_4^+ and urea were 0.1 μmol L^{-1} (Gandhi et al., 2011b).

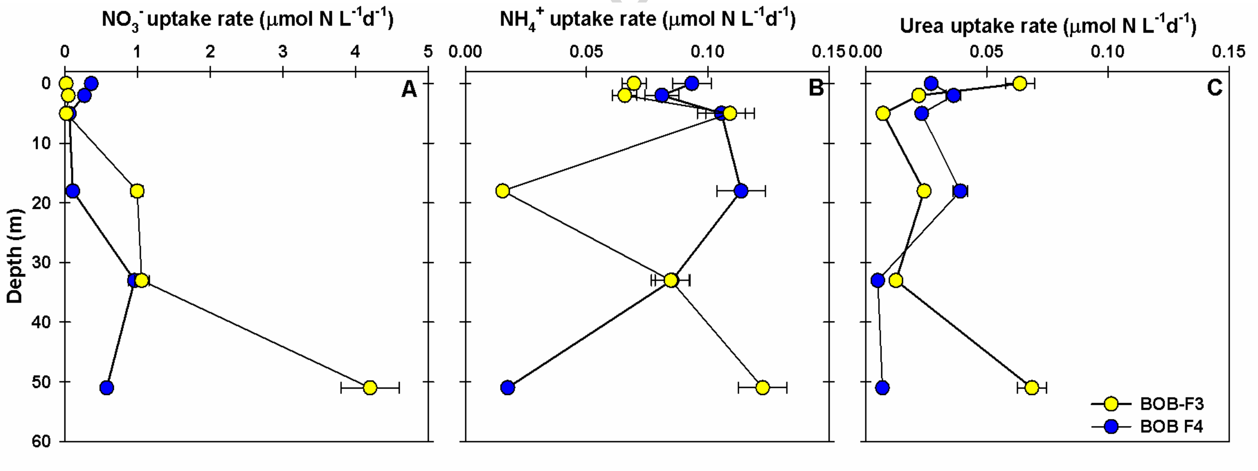

Figure 7. Depth profiles of A- NO_3^-, B- NH_4^+, and C- urea uptake rates at different locations in the Bay of Bengal. Errors associated with the values are 1-sigma standard deviation

As discussed earlier, the uptake rates of NH_4^+ and urea were based on conservative estimates. Surface NH_4^+ uptake rates were comparable at both locations (Fig. 7B) and was 0.08 ± 0.02 μmol N L^{-1} d^{-1}, which was lower than the average NO_3^- uptake rate (0.19 ± 0.24 μmol N L^{-1} d^{-1}). As in the case of NO_3^-, higher values were associated with the deeper depths at BOB-F3. Euphotic-depth-integrated NH_4^+ uptake rate was slightly higher at BOB-F4 than that at BOB-F3

(Table 2). This was in contrast with carbon uptake and new production, both of which showed higher values at BOB-F3. Urea uptake rate at the surface at BOB-F3 was half that of BOB-F4 (Fig. 7B). The average surface urea uptake rate was 0.05 ± 0.03 μmol N L^{-1} d^{-1}, which was lower than the average NO_3^- and NH_4^+ uptake rates. As in the cases of NO_3^- and NH_4^+, higher values were seen at mid-depths at BOB-F3. In contrast to NH_4^+ uptake, the euphotic-depth-integrated values of urea uptake were slightly higher at BOB-F3 than that BOB-F4 (Table 2).

As the NH_4^+ and urea uptake rates were the conservative estimates, the *f*-ratio was likely over estimated. Therefore, *f*-ratio was re-calculated using labeled and unlabelled uptake rates of NH_4^+ and urea by assuming their ambient concentrations to be ~0.1 μmol L^{-1} (see Gandhi et al., 2011b). The re-calculated *f*-ratios at BOB-F3 and BOB-F4 were 0.7 and 0.4, respectively (Table 2).

4. Discussion

4.1. Role of eddies in nutrient cycling in the Bay of Bengal

Riverine nutrient supply is limited to the coast while euphotic surface layers in the open Bay of Bengal are poor in nutrients. Atmospheric deposition of nutrients has but a minor contribution to productivity in this region (e.g., Singh et al., 2012). Neither upwelling nor convective mixing is prominent in this region, mainly due to the upper ocean stratification. Summer upwelling along the western Bay becomes insignificant due to simultaneous downwelling caused by Ekman pumping (Shetye et al., 1991). However, at times, eddies and episodic cyclones may supply nutrients to surface in the Bay (Madhu et al., 2002; Prasanna Kumar et al., 2004), the quantitative assessment of which is yet to be done. Long-term nitrate data suggest several mesoscale eddy-like variabilities within the euphotic zone (Narvekar and

Prasanna Kumar, 2014). The mismatch between this long-term nitrate and chlorophyll indicated the inadequacy of the available data to fully unravel its coupling to mixed layer processes.

In the present study, the northern sampling locations in the Bay of Bengal provided information about the influence of varying river discharge on biogeochemistry, while the southern locations gave an opportunity to study physical, chemical and biological differences within and outside a cyclonic eddy. Locations of BOB-F3 and BOB-F4 were relatively far from the river influence. Sea surface height anomaly, high salinity and low nutrients indicate that BOB-F4 was neither influenced by eddy nor by river discharge. No significant difference in surface NO_3^- was observed between BOB-F3 and BOB-F4 (Fig. 5), which suggests two possibilities, i.e.; either the mixing was limited to the sub-surface layers or the region was N-limited prior to the development of the eddy and the supplied nutrients were consumed by phytoplankton immediately. NO_3^- at 60 m depth in BOB-F3 and BOB-F4 was 14 µM, 7 µM, respectively. NO_3^- value above 40 m in BOB-F3 was 5 µM. Comparing NO_3^- values at 40 m with 60 m depth at BOB-F3 and further with 60 m at BOB-F4 would suggest at least 100% increase in NO_3^- at BOB-F3 that can be attributed to the eddy, which has further enhanced new production at BOB-F3 compared to BOB-F4 by similar (100%) margin. Prasanna Kumar et al. (2007) reported that cyclonic eddies were unable to break the stratification of the top 20 m during fall 2002 and spring 2003. If this was the case, then no significant difference would have been seen between BOB-F3 and BOB-F4 for surface chlorophyll *a* and C-uptake rates. On the contrary, higher chlorophyll *a* and C-uptake rates were observed in the surface layers at BOB-F3 compared to BOB-F4. Although rivers bring nutrients, they are consumed in the estuary or coastal regions and are less likely to influence the southern locations of the Bay of Bengal (e.g., Singh and Ramesh, 2011). N-limited conditions were also reported earlier during the winter in this region (Gomes et al., 2000). Therefore, it is plausible that river-borne nutrients did not reach this location and N-limited conditions were present prior to the development of the eddy. Under N-limited environment in the surface layers, nutrients would be consumed immediately as soon as they are supplied by eddy pumping. Low N:P and N:Si ratios along with the higher chlorophyll *a* and C uptake in the first 20 m at BOB-F3 support this inference. Therefore, it might be concluded that eddies supply nutrients to the stratified surface layers of the Bay of Bengal.

4.2. Primary production in the Bay of Bengal

Biogeochemistry of Bay of Bengal is poorly understood. Limited observations suggest a maximal primary production of 1229 mg C m^{-2} d^{-1}, triggered by a cyclone in the Bay of Bengal (Madhu et al., 2002). Winter blooms occur largely in the southwestern Bay of Bengal (Vinayachandran and Mathew, 2003). Primary productivity does not vary seasonally in the Bay, unlike the Arabian Sea. Nonetheless, there are random peaks in primary production in the Bay that are caused by episodic climatic events (Madhu et al., 2002). Eddies have been suggested to enhance productivity by a factor of two (Prasanna Kumar et al., 2007). Sinking organic carbon is higher in the Bay because of its association with clay minerals, as according to the ‘ballast hypothesis’ (Ittekkot et al., 1991; Kumar et al., 1998). On the other hand, Prasanna Kumar et al. (2010b) showed that although the riverine flux enhanced the nutrients in the euphotic layers during summer, the associated sediment load curbed the downward penetration of sunlight in the north coastal Bay of Bengal. A recent study suggested that 42% of the exportable carbon in the Bay of Bengal is contributed by eddies via diatom bloom (Vidya and Prasanna Kumar, 2013).

Depth profiles of C uptake rates showed higher productivity near the surface and a gradual decrease with the depth (Fig. 6A). Although the Bay of Bengal receives minimum light during winter (Narvekar and Prasanna Kumar 2006), phytoplankton population are rather limited by nutrients (Gomes et al., 2000). Even though the supply of nutrients by eddy-pumping is higher in the sub-surface (Prasanna Kumar et al., 2007), productivity is lower at those depths. Light limitation in the deep is likely responsible for the observed lower productivity, as is also observed during the late winter in the northeastern Arabian Sea (Gandhi et al., 2011a). Euphotic-depth-integrated production was found to be more than twice at BOB-F3 than that BOB-F4. Wind patterns are not significantly different at BOB-F3 and BOB-F4 (Fig. 2). This points to the role of eddy in enhancing productivity at BOB-F3.

Gomes et al. (2000) found off-shore production of ~300 mg C m^{-2} d^{-1} during winter in a non-eddy area in the northern Bay of Bengal, which is consistent with that observed in the present study away from the eddy. Productivity in the eddy (BOB-F3) was 35.8 ± 3.3 mmol C m^{-2} d^{-1} (430 ± 40 mg C m^{-2} d^{-1}), which is similar to values ~500 and ~425 mg C m^{-2} d^{-1} associated with an eddy during fall and spring in the central Bay of Bengal, respectively (Prasanna Kumar et al., 2007).

4.3. New production in the Bay of Bengal

Records of new production in the Bay of Bengal are even less. Kumar et al. (2004) suggested average new production to be 36 mmol C m^{-2} d^{-1} in the Bay, which is as high as that observed in the Arabian Sea. Present study suggests that an eddy can increase new production by more than twice in this region (Table 2). There is an increase in NO_3^- uptake following the increase in NO_3^- concentrations at increasing depths. This is in sharp contrast with the C uptake rate profiles, which showed higher uptake in the surface layers at these locations. This indicates that the productivity in the surface layers was fueled by non-nitrate nitrogen. In the top 10 m, the *f*-ratio was ~0.2 at both locations, which indicates that the NO_3^- uptake was lower than the uptake of reduced forms of nitrogen (i.e., NH_4^+ and urea). Denitrification is not prominent in the Bay of Bengal (Howell et al., 1997) and thus, the deeper waters in the Bay of Bengal are in general not depleted in NO_3^-. Therefore, as a result of eddy pumping, deeper water would advect oxidized forms of nitrogen (e.g., NO_3^-) to the surface. This was reflected in the observed higher NO_3^- uptake and lower uptake rates of reduced forms of nitrogen (NH_4^+ and urea) in the layers deeper than 10 m. Deeper layers exhibited very high NO_3^- uptake and *f*-ratio and higher NO_3^- uptake and *f*-ratio were observed at BOB-F3 compared to BOB-F4 (Table 2). The present results corroborate earlier observations that the productivity switches from 'regenerated' to 'new' production during the presence of eddies in the Bay of Bengal (Muraleedharan et al., 2007). Kumar et al. (2004) also reported *f*-ratios 0.3-0.8 and 0.5-0.7 with the higher values associated with eddies during the fall 2002 and spring 2003 in the central Bay of Bengal. In the light of above discussion, it is surmised that eddy-pumping has the potential to enhance new production locally. This has implications in understanding the export production in the Bay of Bengal and Arabian Sea, as indicated by sediment trap data, despite the production in the former being lower (Ittekkot et al., 1991; Lee et al., 1998).

4.4. Global significance of this study and outlook

Our study suggests that influence of eddies on new and primary productivity is higher in the Bay compare to what has been observed in the subtropical Pacific and Atlantic Ocean. Eddies could increase productivity by 20% and 15% in the in the subtropical Pacific and Atlantic Ocean

(Falkowski et al., 1991; Oschlies and Garcon, 1998), while we have observed 100% increase in the new and primary production. This underscores the global importance of eddies in the Bay of Bengal in exporting the carbon flux. However, our results cannot be extrapolated to the entire Bay of Bengal as influence of eddies varies spatially. We also note that eddies do not necessarily increase export production, as has been reported from other parts of the world ocean (e.g., Benitez-Nelson et al., 2007; Maiti et al., 2008). Eddies suppress export flux in the eastern boundary upwelling systems (Gruber et al., 2011). Though the Bay of Bengal is not a coastal upwelling region but we do not know much about the biogeochemistry of this region so our results need to be confirmed by more such data.

There is still a mismatch in the geochemical and biological estimates of new (export) production. Geochemical estimates (based on rates of oxygen exchange or heat fluxes) are two to three times higher than those estimated by biological measurements. It was suggested that the mismatch could be because biological estimates undersample episodic events such as eddies. However, biological estimates made during eddies still could not reach to level of geochemical estimates in the subtropical Pacific and Atlantic Ocean (Falkowski et al., 1991; Oschlies and Garcon, 1998). Nonetheless, observations in the oligotrophic regions (the Sargasso Sea) suggest that nutrient flux from the deeper ocean via eddies can sustain new production in the euphotic ocean (McGillicuddy and Robinson, 1997, McGillicuddy et al., 1998). Furthermore, nutrient flux via eddies causes plankton blooms in the Sargasso Sea and increases new production up to three times (McGillicuddy et al., 2007). The Bay of Bengal is an oligotrophic region akin to the Sargasso Sea. Despite of being oligotrophic, blooms were reported in the Bay of Bengal (Vinayachandran and Mathew, 2003) but the reasons have not been clarified. More studies during eddies in this region are called for to understand the bloom dynamics.

Eddies are mostly transient and propagate steadily. But as they pass by, it is difficult to capture their imprints on biogeochemical changes as these may or may not be visible immediately. We require both Lagrangian and Eulerian observations in the eddies for better understanding of their influence on biogeochemical cycles.

5. Conclusion

Two locations in the northern Bay of Bengal indicated the influence of varying river discharge on biogeochemistry, and the other two locations provided an opportunity to study physical, chemical and biological differences within and outside an eddy. Nutrients were brought by river influx to the northern locations. The freshwater input shallowed mixed layer depth, which increased primary production in the region. Lower mixed layer depth provided a better environment for productivity by restricting plankton to the better lit upper layers. Sea surface height anomaly data suggested that one of the southern locations was influenced by an eddy. Shallowing of the thermocline and halocline by 10 m was noticed within (BOB-F3) compared to outside (BOB-F4) the eddy. Mixed layer depth also shoaled at the eddy compared to outside. Despite these differences, no significant difference between within- and outside-eddy locations was observed for surface NO_3^-. However, higher chlorophyll *a* and primary production were observed at the eddy relative to outside. Further, the eddy supplied nutrients to the surface layers, thus shallowing the subsurface chlorophyll maximum. Euphotic-depth-integrated production was more than twice within the eddy than that at outside. This confirmed the role of eddies in enhancing productivity in the Bay of Bengal. Higher new production and *f*-ratios observed within the eddy suggested that eddies contribute to higher than normal export flux. Our results suggest that even moderately productive oceanic regions such as the Bay of Bengal, may be capable of higher new production.

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Highlights:

1. First direct measurements of new production in an eddy in the Bay of Bengal.

2. 100% increase in nutrient concentrations is seen due to the eddy.

3. Eddy enhanced new and primary production in the otherwise less productive Bay of Bengal.