

Lack of seasonality in phytoplankton standing stock (chlorophyll a) and production in the western Bay of Bengal

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Abstract

The investigations in the western Bay of Bengal (BoB) during summer, winter and spring intermonsoon periods evidenced lack of pronounced seasonal variation in phytoplankton standing stock (chlorophyll a) and primary production. The supply of riverine materials to the coastal bay is witnessed by the presence of major nutrients (nitrate - NO₃, phosphate - PO₄ & silicate - SiO₄) in the upper layers (up to 20meters) during monsoonal periods. However, it was not found to enhance the phytoplankton production rates to a large extent. The strong stratification due to enormous quantity of fresh water discharge, acts as a barrier to vertical transport of nutrients from the subsurface layers. The average primary production in the inshore and the offshore waters of the BoB were 350 ± 225 and 251±177 mgCm⁻² d⁻¹ in summer, 252 ± 210 and 231 ± 150mgCm⁻²d⁻¹ in winter and 308 ± 120 and 303 ± 95 mgCm⁻²d⁻¹ in spring intermonsoon periods, respectively. Subsurface chlorophyll maxima (SCM) were observed at 20-50m in the spring intermonsoon, whereas in summer and winter, the chlorophyll maxima occurred in the upper layers of the euphotic zone (<20m). The vertical distribution of phytoplankton (>5µm) was primarily restricted by the pycnocline, and the bulk of phytoplankton assemblage existed within the surface. The seasonal change in cell numbers, however, did not coincide closely with the changes in the chlorophyll a concentration. Diatoms formed the major group (>85%) in the total phytoplankton abundance irrespective of seasons. During spring intermonsoon, large patches of *Trichodesmium* blooms were observed in the coastal as well as open waters of the western BoB.

Key words: - Bay of Bengal; Chlorophyll a; Primary production; *Trichodesmium*; Upwelling; Thermal inversion

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Introduction

The Bay of Bengal (BoB) located between 0° and 23°N and 80° and 100°E and occupying an area of $4.087 \times 10^6 \text{ km}^2$ is a region of positive water balance. It hosts a unique system of inter-related oceanographic and sedimentary processes induced by the seasonally reversing monsoon winds and the enormous supply of fresh water ($1.5 \times 10^{12} \text{ m}^3$) and silt ($16 \times 10^8 \text{ t/y}$) from several peninsular Indian rivers (Shetye et al., 1996). The freshwater influx induces estuarine characteristics over large areas of the bay, which impedes exchange between the surface and deep waters with consequent impact on biological processes. Rainfall over BoB shows wide spatial variability and strong seasonality: the southeast coast of India has a winter rainfall maximum, whereas the rest of the BoB has a summer monsoon maximum (Ramage, 1984). During summer, large fresh water discharge from the north Indian rivers substantially lowers the salinity and also reduces the intensity of upwelling $\sim 40\text{km}$ from the coast (Shetye et al., 1991). This enormous fresh water input causes strong vertical stratification (barrier layer) inhibiting the upliftment of nutrients (Sprintall and Tomczak, 1992; Vinayachandran et al., 2002, Maheswaran, 2004). For example, even though the SST in the northern bay is low (25°C) during winter, convective overturning is prevented by the stability induced by low saline (<30) surface waters (Jyothibabu et al., 2004; Maheswaran, 2004).

Conventionally BoB is believed to be relatively less productive compared for example with the neighboring Arabian Sea - AS (Qasim, 1977; Radhakrishna et al., 1978; Prasannakumar et al., 2002; Madhu, 2004). The seasonal (upwelling and cold core eddy) and some sporadic events (cyclones) enhance moderate phytoplankton production of the BoB in some areas (Gomes et al., 2000; Madhu et

al., 2002; Prasannakumar et al., 2004). During spring intermonsoon, eddies and recirculation zones form in the coastal region of the bay due to the western Bay of Bengal current (WBC) found to enhance phytoplankton growth to some extent (Gomes et al., 2000; Prasannakumar et al., 2004). Where as in monsoon seasons (summer & winter), the nutrient inputs from river runoff, trigger primary production of the coastal waters of the BoB (Gomes et al., 2000; Madhu et al., 2002; Madhupratap et al., 2003). Based on a new and systematic data set, the present study investigates the seasonal change in phytoplankton biomass and primary production in the western BoB with respect to the prevailing physico-chemical environment.

Materials and Methods

The data were collected from the western BoB (Fig. 1) during spring intermonsoon (April 2000), winter monsoon (December 2000) and summer (July/August 2002) seasons as a part of the project “Marine Research - Living Resources (MR-LR) Assessment” programme funded by Department of Ocean Development (DOD), Govt of India. Winds were monitored by the automated weather station on board the ship. Temperature and salinity were determined from Sea-Bird Electronics CTD (USA, model: SBE-911 plus) data and the sea surface temperature (SST) was measured using bucket-thermometer. The mixed layer depth (MLD) was determined from density profiles as the depth at which the density difference from the surface was 0.2kgm^{-3} . Similarly, the barrier layer was considered as the layer between the base of the mixed layer and the top of the thermocline (Sprintall and Tomczak, 1992). The water samples for nutrients were collected up to 150 meters (ie, 0, 10, 20, 50, 75, 100 & 150meters) using 5-litre Niskin samplers and

analyzed with a SKALAR auto-analyser (Model SA - 1050). For the estimation of chlorophyll *a* and primary production, water samples were collected from discrete depths such as 0, 10, 20, 50, 75, 100 & 120 meters. One-litre seawater samples from each depth were filtered through Whatman GF/F filters (nominal pore size 0.7 μm) to determine chlorophyll *a* using a Perkin-Elmer UV/Vis spectrophotometer (Strickland and Parsons, 1972). Primary production was estimated by *in-situ* method using the ^{14}C - technique (UNESCO 1994). Seawater samples were collected before sunrise from seven depths mentioned above. Water samples were immediately passed through 200 μm plankton net to remove large sized zooplankton and transferred to 300ml capacity Nalgene bottles. After the inoculation of $\text{NaH}^{14}\text{CO}_3$ (activity 5 μC), the light and dark bottles were deployed *in-situ* in a mooring system for 12 hours. The experiments were terminated by filtering the samples on to 47mm Whatman GF/F filters and the filters were used for subsequent analysis in liquid scintillation counter after treatment with HCl fumes to remove inorganic carbon. The primary productivity rate was calculated according to the equation described in the protocol. The chlorophyll *a* specific primary production was determined by taking the production value and dividing it by the respective chlorophyll *a* concentration, generating units of $\text{mgC mgChl } a^{-1} \text{ hr}^{-1}$

For qualitative studies of phytoplankton (>5 μm), 500ml of seawater samples drawn from the depths mentioned above were fixed in 1% Lugol's iodine and preserved in 3% formaldehyde solution. The samples were stored in the dark at low temperature until enumeration within a period of one month after collection. A settling and siphoning procedure was followed to obtain 20-25ml concentrates. One ml of this concentrated sample was examined microscopically in triplicate under a

stereoscope binocular microscope (magnification 100x) in a Sedgewick-Rafter counting chamber. Chain-forming cells were counted on a per cell basis and empty cells were excluded. As far as possible, the phytoplankton groups were identified to species, but in some taxonomic groups, identification is confined to genera. Taxonomic criteria and diagnosis for phytoplankton identification mainly relied on Subrahmanyam (1959) and Tomas (1997).

Results

Hydrography and chemistry

During summer monsoon, the winds were predominantly south-westerlies and occasional north-westerlies with the magnitude often exceeding 6ms^{-1} (Figs. 2a, 3a & 3b). SST did not show much variation between inshore (av. 29.5°C) and offshore (av. 29.4°C) waters (Figs. 3c & 3d). A northward decrease in SSS and sigma - t was observed in inshore, as well as offshore waters (Figs. 3e, 3f, 3g & 3h). MLD was relatively deep ($>40\text{m}$) in the southern region and shallow in the north, where as the barrier layer thickness was less ($<20\text{m}$) in the south as compared to north (Figs. 3i & 3j, 3k & 3l). The vertical distribution of temperature shows upsloping of isotherms above 50m, which indicates the signatures of upwelling at 15°N inshore waters (Fig. 4a). Similarly, the vertical structure of salinity and sigma - t were evidenced a sharp south-north gradients in the upper 50m due to the fresh water influx from the north (Figs. 4c, 4d, 4e & 4f). Low concentration ($<200\mu\text{M}$) of dissolved oxygen (DO) was observed in the upper layers of the entire study area during summer (Figs. 5a & 5b). Inshore region was characterized by shallow nitracline ($\sim 20 - 30\text{m}$), but it was slightly deeper ($\sim 50\text{m}$) offshore (Figs. 5c & 5d).

Similarly, traces of inorganic phosphate ($\sim 0.4\mu\text{M}$) and silicate ($\sim 1\mu\text{M}$) could also be noticed in the upper 50m of northern inshore waters, while it was lacking in offshore (Figs. 5e, 5f, 5g & 5h). Besides that, the upward shift of isolines of nitrate and phosphate in the 15°N inshore waters, strongly support the signatures of upwelling.

Generally, weak winds (av. 3.7 ms^{-1}) were prevalent in the study area during winter monsoon (Figs. 2b, 3a & 3b). Inshore SST showed a warming trend towards north upto 15°N , thereafter it decreased and showed a minimum ($\sim 26.0^\circ\text{C}$) at 20.5°N (Figs. 3c & 3d). Whereas in the offshore, SST showed a steady decrease towards north (a gradient of 2.2°C from 11°N to 20.5°N). Similarly, SSS also showed a steady decrease of ~ 4 from 11°N to 20.5°N in the offshore region but inshore SSS showed a fluctuating trend from north to south (Figs. 3e & 3f). Prominent south-to-north decrease in surface sigma- t was observed both inshore as well as offshore waters (Figs. 3g & 3h). Generally, MLD was shallow all over the area (inshore av. 20m & offshore av. 33m) during this season, while the barrier layer was relatively thicker ($>40\text{m}$) in the inshore-offshore waters of northern region (Figs. 3i, 3j, 3k & 3l). Distinct thermal inversion was observed in the north with relatively cold surface waters ($<28^\circ\text{C}$) overlying the warm ($>28^\circ\text{C}$) subsurface layers (Figs. 4g & 4h). Vertical structure shows inshore waters characterized by low salinity (<30) with low density (<20), which found to spread over 30m in the entire coast (Figs. 4i & 4k). But in offshore, the low salinity waters were restricted in the north (Figs. 4j & 4l). DO was saturated in the surface layers of both inshore ($>200\mu\text{M}$) and offshore waters (Figs. 5i & 5j). Traces of inorganic nutrients (nitrate, phosphate and silicate) were observed above 50m inshore waters as compared to offshore (Figs. 5).

During spring intermonsoon, strong winds ($\sim 12 \text{ ms}^{-1}$) were observed in the northern inshore (especially 19° & 20.5°N) region of the BoB (Figs. 2c, 3a & 3b). SST showed relatively high values in the entire area ($>29^\circ\text{C}$) and the inshore-offshore variability in SST was minimum (Figs. 3c & 3d). SSS and surface sigma- t were also found to be high (>32 & >20) during this season compared with the other two seasons (Figs. 3g, 3h, 3i & 3j). Shallow MLD (2 - 30m) and thin barrier layer ($<15\text{m}$) was observed all over the area during this season (Figs. 3i, 3j, 3k & 3l). Vertical distribution of temperature in the upper layers showed an upsloping towards north and also strong thermal stratification (Figs. 4m & 4n). The vertical salinity structure in the upper layers shows relatively high salinity (33 - 35.5) with minimum gradients due to the reduction in fresh water (Figs. 4o & 4p). The vertical density structure shows more similarity to temperature structure (Figs. 4q & 4r). High concentration of DO ($>200\mu\text{M}$) evidenced in the upper layers of both inshore and offshore waters (Figs. 5q & 5r). A relatively deeper nutricline ($\sim 50\text{m}$) was also a characteristic feature in the upper layers during this season (Figs. 5s & 5t, 5u, 5v, 5w & 5x).

Chlorophyll a

During summer, inshore waters exhibited somewhat higher chlorophyll *a* concentration (surface av. $0.43 \pm 0.6 \text{ mgm}^{-3}$; column av. $21.9 \pm 16.8 \text{ mgm}^{-2}$) in the BoB than the corresponding offshore waters (surface - $0.19 \pm 0.08 \text{ mgm}^{-3}$, column - $14.1 \pm 6.3 \text{ mgm}^{-2}$). Southern inshore waters showed low chlorophyll *a* ($<0.1 \text{ mgm}^{-3}$) as compared to the northern inshore. Moreover, an anomalous increase in chlorophyll *a* (surface - 1.4 mgm^{-3} ; column - 42.8 mgm^{-2}) was observed at 15°N

coastal waters, which supports the biological signatures of upwelling. The chlorophyll maxima was mostly confined to <20m at most of the stations, which indicated the absence of subsurface chlorophyll maxima (SCM). The average chlorophyll *a* (both surface and column) showed slightly higher values in the inshore waters than the corresponding offshore (Figs 6a & 6b). During winter monsoon season, the chlorophyll *a* showed a more or less similar trend as observed in summer (inshore av. $0.17 \pm 0.14 \text{ mg m}^{-3}$; offshore av. $0.14 \pm 0.07 \text{ mg m}^{-3}$) although, the integrated column chlorophyll *a* was rather less (inshore av. $13.0 \pm 7.7 \text{ mg m}^{-2}$, offshore av. $11.5 \pm 4.1 \text{ mg m}^{-2}$). Like the summer monsoon, the chlorophyll maxima also found to remain in the surface layers (0 - 20m) during winter (Fig 7). Spring intermonsoon showed relatively less concentration of surface chlorophyll *a* (av. $<0.3 \text{ mg m}^{-3}$) in the entire region, while the integrated column chlorophyll *a* was comparable with summer and winter monsoon seasons (Figs. 6a & 6b). The SCM was slightly deeper (~50m) during spring intermonsoon in contrast to summer and winter monsoon (Fig 7).

Primary production

During the summer monsoon, similar to chlorophyll *a* distribution, the BoB had lower production rates in the southwest region than the northwest, except the inshore waters off 15°N. The average surface primary production showed a two-fold increase between the inshore (av. $16.1 \pm 18.4 \text{ mgC m}^{-3} \text{ d}^{-1}$) and offshore waters (av. $7.5 \pm 7.1 \text{ mgC m}^{-3} \text{ d}^{-1}$; Fig 6c). Whereas the integrated column primary production did not show much variability (inshore - $350 \pm 225 \text{ mgC m}^{-2} \text{ d}^{-1}$ & offshore - $251 \pm 177 \text{ mgC m}^{-2} \text{ d}^{-1}$). Maximum surface primary production was recorded off 15°N inshore

(45.8 mgC m⁻³d⁻¹), but the maximum column primary production (621mgC m⁻²d⁻¹) was observed at inshore waters off 20.5°N. During the winter monsoon, the average surface primary production showed a similar trend to that observed in summer; but the rate of production appeared less (inshore av. 8.6 ± 10.6 mgC m⁻³ d⁻¹; offshore av. 4.0 ± 2.6 mgC m⁻³ d⁻¹; Figs. 6c & 6d). On the other hand, the average water column primary production was more or less similar in inshore (av. 252 ± 210 mgC m⁻² d⁻¹) and offshore (av. 231±150mgC m⁻² d⁻¹). Like chlorophyll *a*, the average primary production rates during spring intermonsoon was relatively less (av. <6mgCm⁻³d⁻¹) in the surface compared to other two seasons, while the average integrated column primary production appears to slightly high (av. 305mgC m⁻²d⁻¹) compared to summer and winter monsoon seasons (Figs. 6c & 6d).

Chlorophyll a specific primary production

The values of chlorophyll *a* - specific primary production, an index of phytoplankton growth rate (Lalli and Parsons, 1993) also did not show marked seasonal variations. The average values of chlorophyll *a* - specific primary production in the inshore surface waters were 3.1 ± 1.5, 2.1± 0.3 and 2 ± 1mgC mgChl *a*⁻¹ hr⁻¹ respectively, during summer, winter and spring intermonsoon periods. While in the offshore, the corresponding values were 2.8 ± 2.8, 3.4 ± 5.2 and 2.5 ± 1.6 mgC mgChl *a*⁻¹ hr⁻¹, respectively.

Phytoplankton abundance and composition

Eighty-six species of phytoplankton (diatoms - 68 species and dinoflagellates - 17) from various depths were encountered during summer (Table 1). The

abundance in the surface was relatively higher inshore (av. 15227 cells l⁻¹) compared to offshore (av. 4039 cells l⁻¹). The abundance in the vertical water column was also more inshore (av. 151.63 x 10⁶ cells m⁻²) than the offshore (av. 121.34 x 10⁶ cells m⁻²). Generally, diatoms formed the major component (88 - 99%) of the total phytoplankton density followed by dinoflagellates (1 - 10%). Among diatoms, the pennate group showed the dominance (av. 71 x 10⁶ cells m⁻²) over the centric group (av. 42.9 x 10⁶ cells m⁻²). The genus *Thalassionema* formed the most abundant group (*Thalassionema frauenfeldii* ca. 42% & *Thalassionema nitzschioides* ca. 23%) in the upwelled waters (15°N). Other dominant groups encountered during this period were, *Rhizosolenia delicatula*, *Nitzschia seriata*, *Nitzschia closterium*, *Navicula directum*, *Coscinodiscus* sp., *Biddulphia sinensis*, *Ditylum brightwelli*, *Skeletonema costatum* etc and the dinoflagellates were *Ceratium furca*, *Prorocentrum* sp., *Oxytoxum scolopex*, *Peridinium* sp., *Dinophysis* sp., etc.

During the winter monsoon, similar to the summer monsoon, the diatoms constituted 91 to 95.4% in the total phytoplankton population, followed by dinoflagellates (0.9 - 7.2%). Pennate diatoms (av. 85.9 x 10⁶ cells m⁻²) dominated over centrals (av. 71 x 10⁶ cells m⁻²) in total diatom density. The dominant diatom species encountered during this season were *Thalassionema nitzschioides*, *Skeletonema costatum*, *Coscinodiscus* sp., *Thalassiothrix longissima*, *Nitzschia seriata*, *Chaetoceros* sp., *Rhizosolenia* sp., etc and the dinoflagellates were *Prorocentrum* sp., *Ceratium macroceros*, *Ceratium bucephalum*, *Ceratium furca*, *Ornithocercus* sp., *Gymnodinium* sp., *Gonyaulax* sp. (Table 2).

Extensive thick patches of *Trichodesmium erythraeum* blooms (Plates 1a, 1b & 1c), characteristic feature of oligotrophic tropical and subtropical waters were

encountered in the open waters (off Karaikkal - 10°58' N; 81°50'E and off south of Calcutta - 19° 44'N, 89° 04'E) and also some coastal region (thin patches only) of the BoB during the spring intermonsoon. Eventhough, in general the total phytoplankton abundance was relatively low in the BoB, the bloom area shows high numerical abundance due to proliferation of *Trichodesmium erythraeum*. The numbers of phytoplankton taxa were also less during this period, (diatoms - 42, dinoflagellates - 10, others - 3) compared to other seasons. On an average, the diatoms constituted <88% in the study area, followed by dinoflagellates (7.5%). The diatoms, *Nitzschia seriata* and *Skeletonema costatum* were most common in inshore, where as in the open ocean waters *Chaetoceros* sp., *Rhizosolenia* sp. and of some other times *Trichodesmium erythraeum* were also found to dominate during this period. Other species were *Thalassionema nitzschioids*, *Thalassionema frauenfeldii*, *Pleurosigma* sp., *Thalassiothrix longissima*, *Navicula* sp., etc. The major dinoflagellates were *Prorocentrum* sp., *Ceratium bucephalum*, *Ceratium macroceros*, *Ornithocercus* sp., *Peridinium* sp. etc.

Discussion

During summer, the direction of the wind along the coast was favourable for offshore-wind driven Ekman transport that would drive upwelling along the coast (Fig 2). However, the signatures of upwelling such as cold waters, shallow mixed layer, upsloping of isolines of temperature, salinity, density and nitrate towards the coast were evident only at 15°N (Figs. 4 & 5). The enormous fresh water discharge from the north (Ganges - Brahmaputra - Mahanadi river system) leads to the formation of a salinity front at the outer edge of an upwelling front, which is

responsible for an equatorward flow that found to overwhelm the upwelling in the north during summer (Gopalakrishna and Sastry, 1985; Shetye et al., 1991). Murty and Varadachari (1968) and de Sousa *et al.*, (1981) reported localized mild upwelling along the southern part of the western boundary of BoB in summer. Shetye et al (1991) stated that upwelling along the east coast was normally found to be restricted ~ 40km wide band, and delineate the structure of the upwelling band and its transition from south to north along western BoB. The shallow nitracline (~20 to 30m) in inshore waters might be partly due to river discharge and partly upwelling process (Figs. 5c). Besides that, high concentration of nutrients (nitrate -1 μ M, phosphate - <0.4 μ M and silicate - <2 μ M) found in the upper layers of the northern inshore (20.5°N) waters substantiates the enormous riverine input during summer.

The increase in primary production (surface - 45.8 mgC m⁻³ d⁻¹; column - 470 mgC m⁻²d⁻¹), chlorophyll *a* (surface - 1.4mgm⁻³; column - 42.8mgm⁻²) and total phytoplankton abundance (surface - 52550 cells l⁻¹; column - 439.39 x 10⁶ cells m⁻²) at 15°N inshore waters, strongly support the biological evidence for upwelling, even though the upwelling induced primary production was relatively less in the BoB as compared with the west coast of India (Bhattathiri et al., 1996, Madhu, 2004). Radhakrishna et al, (1978) reported a wide range in chlorophyll *a* (surface - 0.08 to 1.67mgm⁻³; column - 8.6 to 28.5 mgm⁻²) in the western BoB during 1976 summer. For 1978 summer, Bhattathiri *et al.*, (1980) also reported similar chlorophyll concentrations (surface - 0.01 to 1.01 mgm⁻³, column - 1.3 to 33.7mgm⁻²) in the area. Even though some areas in the western BoB showed high concentrations of chlorophyll *a* (av. >100mgm⁻²), these values did not lead to high productivity of the area due to cloud cover (Gomes et al., 2000). Similarly, surface productivity

maxima in BoB can be observed only during the summer monsoon, when the light level was very low ($500\mu\text{Em}^{-2}\text{s}^{-1}$). The studies of Madhu et al (2002) recorded low phytoplankton biomass and production in the continental shelf (av. 8mgm^{-2} & $289\text{mgC m}^{-2}\text{d}^{-1}$) and offshore waters (8.2 mgm^{-2} & $240\text{ mgC m}^{-2}\text{d}^{-1}$) of southeast coast of India in summer. Recently, as a part of Bay of Bengal Process Studies (BOBPS), Madhupratap et al, (2003) reported relatively high primary production in the open waters (328 to $520\text{mgC m}^{-2}\text{d}^{-1}$) compared to the coastal waters (90 to $220\text{ mgC m}^{-2}\text{d}^{-1}$) of the BoB.

Apart from the upwelling-induced primary production (15°N), moderate levels of production were also observed in the northwestern BoB (19 & 20.5°N) in summer. The higher phytoplankton biomass (36.6mg m^{-2}) and production ($621\text{mgC m}^{-2}\text{d}^{-1}$) in the north (especially inshore waters off 20.5°N) was also reflected in the total phytoplankton population density (244.92×10^6 cells m^{-2}). Diatoms, the most abundant group (99.3%) were dominated (239.46×10^6 cells m^{-2}) in the low saline waters of the north, perhaps because of the riverine supply of silicate ($\sim 2\mu\text{M}$) in the surface layers as compared to the concentration of nitrate (Fig. 4g). This is substantiated by the reports of De et al., (1991), which showed that the concentration of dissolved silica is high in the north compared with that of dissolved nitrate. In summer, a significant linear correlation ($P < 0.01$) was observed in the phytoplankton biomass with primary production (inshore - $r = 0.787$; offshore - $r = 0.612$) and phytoplankton density (inshore - $r = 0.557$; offshore - $r = 0.063$), except for the insignificant relation of chlorophyll *a* with phytoplankton density in the offshore region (Figs. 8a, 8b, 8c & 8d).

Thermal inversion, the prominent feature in BoB during winter was more pronounced ($>3^{\circ}\text{C}$) in the north, while in south it was relatively less ($\sim 0.5^{\circ}\text{C}$; Fig 9). Many authors have reported the phenomenon of thermal inversion in the BoB (Shetye et al., 1996; Han et al., 2001; Pankajakshan et al., 2002, Maheswaran 2004). Shetye et al. (1996) suggested that the process of inversion in the BoB starts in the north during summer monsoon and accelerates with the onset of the northeast monsoon, when cold continental winds cool the surface waters of the bay particularly in the north. Nevertheless, though SST is low (ca. 25.8°C) in the north, winter cooling did not lead to convective mixing and enrichment of upper layers in the BoB due to intense stratification by the fresh water cap (Banse, 1984; Prasannakumar and Prasad, 1996; Madhupratap et al., 1996, Jyothibabu et al., 2004). The presence of nitrate ($1\mu\text{M}$) in the surface layers ($<20\text{m}$) of the northern region might be due to the inputs from rivers rather than to winter convective mechanisms (Fig. 5k).

During winter, the southwestern BoB (11°N & 15°N) shows relatively high phytoplankton standing stock and production, compared to the northwest. The low salinity (25.9 - 27.1) in this area was evidenced for the heavy river discharge (Cauvery, Krishna and Godavari) in association with the northeast monsoon rainfall. Similarly, traces of nitrate ($1\mu\text{M}$) in the top 50m inshore waters might have arisen from the riverine input, which ultimately enhances primary production ($566\text{mgC m}^{-2}\text{d}^{-1}$ & $433\text{ mgCm}^{-2}\text{d}^{-1}$) and chlorophyll *a* (21.5 mg m^{-2} & 22.9 mgm^{-2}), and total phytoplankton abundance ($144.5 \times 10^6\text{ cells m}^{-2}$ & $229.40 \times 10^6\text{ cells m}^{-2}$) in 11° and 15°N of southern BoB. Ramage (1971) reported that December - February months bring heavier rainfall to southeastern India than to the northeastern region. Madhu

et al. (2002) reported enhanced primary production (av. $734 \text{ mgC m}^{-2} \text{ d}^{-1}$) in the southeast coast ($11^\circ - 15^\circ \text{N}$) of India in association with the super cyclone that hit to Orissa coast on October 1999 and in general, land run off by the heavy rainfall caused the high nutrient concentrations. Significant linear correlation ($P < 0.01$) was observed between chlorophyll *a* and primary production and phytoplankton abundance during this season (Figs. 8e, 8f, 8g & 8h).

The warm surface water ($>29^\circ \text{C}$) and associated thermal stratification was a well-known feature in the BoB during spring intermonsoon. Shetye et al (1993) observed several warm water recirculation zones in the northwestern BoB, in association with the poleward flow of East India Coastal Current (EICC) north of 10°N , which carry nutrient poor warm water from the south. Similarly, the studies on nutrient distribution in the western BoB showed that during March - April months, rivers flowing in to the BoB might not contribute much to the inorganic nutrient pool (Sengupta et al., 1977; Rao et al 1994). These are the reasons why the upper layers of the BoB are devoid of nutrients in the spring intermonsoon. Obviously, this nutrient depleted condition might have lead to the oligotrophic nature of the BoB in spring. Generally on average, the concentration of chlorophyll *a* and primary production was found to be low in the BoB, but the values seem slightly high (inshore - 15.3 mg m^{-2} & $307 \text{ mgC m}^{-2} \text{ d}^{-1}$ and offshore - 14.1 mg m^{-2} & $303 \text{ mgC m}^{-2} \text{ d}^{-1}$) when compared with winter monsoon (Fig. 6). In addition to less nutrient input, increased irradiance and strong thermal stratification also lead to the low phytoplankton production in the western BoB during spring. The formation of large patches of cyanobacterial blooms (*Trichodesmium erythraeum*) in the coastal as well as open waters substantiated the oligotrophic nature of the BoB during spring intermonsoon.

Nevertheless, the surface waters of the bloom area have traces of inorganic nitrate (0.05 to 0.14M), which may be due to extracellular products when the *Trichodesmium* filaments decay. Relatively high DO (>200µM; Fig. 5) in the upper layers of the bay during spring intermonsoon may be due to the lower respiration rate of organic matter and also the lower particle flux (Rao et al., 1994, Unger et al., 2003).

In general, the seasonal (upwelling and cold core eddies) and some sporadic physical events (cyclones) enhance moderate phytoplankton production of the bay in some areas, although these are only transient effects (Gomes et al., 2000; Madhu et al., 2002; Vinayachandran et al, 2003; Prasannakumar et al, 2004). Eventhough the BoB is oligotrophic, nearly 70% of the phytoplankton standing stock and production exists in the top 50m of inshore (av. $71.2 \pm 18.4\%$, n=17 & $76.4 \pm 16.2\%$, n=17) and offshore (av. $63.2 \pm 9.3\%$, n=18 & $75.9 \pm 10.1\%$, n=18) waters like any other tropical seas (Figs. 10). SCM observed deeper (~50m) depths during spring intermonsoon might be due to the high irradiance and thermal stratification. Where as in summer and winter, the chlorophyll maxima restricted to the surface layers (<20m) and it could be result of reduced light level by the cloud cover in association with the monsoonal rainfall. Studies of Murty et al (2000) showed that a shallow SCM is prevalent in the coastal waters (20-30m) as compared to open waters. Similar to chlorophyll maxima, the primary production maxima were also observed in the surface layers (<20m) especially in the summer and winter monsoon periods, which show a direct response to low irradiance.

Conclusions

The analyses of our data sets reveals that BoB does not exhibit large-scale seasonal and spatial variability in phytoplankton standing stock and production as its western counter part the AS does. Obviously, the non-accessibility of nutrients due to thermal stratification and low riverine input makes the bay oligotrophic during spring intermonsoon. Where as in summer and winter, the nutrients available in the surface layers (above 50m) of inshore waters (brought by the heavy rain fall and associated riverine input) are not utilized by the phytoplankton, possibly due to the increase in turbidity and intense cloud cover. Riverine influx generates not only the increase in turbidity, but also enhance the formation of barrier layers, which prevent convective mixing in the northern bay, even when the atmospheric cooling is evident. Thus, physical processes in the BoB are not strong enough to enhance the phytoplankton growth in a great extent as can be observed in the AS. In addition to that in BoB, the studies of photoautotrophic picoplankton, known as the 'prochlorophytes and cyanobacteria', characteristic feature of oligotrophic tropical and subtropical waters have not been addressed, even though they occupy a key position at the base of the food chain. In future, flow-cytometric studies of prochlorophytes and cyanobacteria will provide much information to the biogeochemical processes and associated carbon fluxes of BoB in detail.

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Bacillariophyceae**Centrales**

Melosira sp.
*Skeletonema costatum**
*Thalassiosira subtilis**
T. hyaline
Stephanopyxis sp.
Cyclotella sp.
Coscinodiscus sp.
C. lineatus
C. nitidus
C. centralis
C. marginalis
Planktoniella sol
Actinopterychus undulatus
Asteromphalus sp.
Aulacodiscus sp.
Corethron sp.
Lauderia annulata
Shroederella sp.
Leptocylindrus danicus
Rhizosolenia sp*.
R. stolterforthii
R. styliformis
R. setigera
R. hebatata
R. alata
R. cylindrus
R. castracanei
Guinardia striata
Bacteriastrum delicatula
B. hyalinum
B. comosum
Cheatoceros sp.
C. diversus

C. affinis
C. curvisetus
C. pelagicus
C. danicus
C. dedymus
C. holsaticus
Eucampia sp.
Hamialus huckii
Climacodium sp.
Ditylum brightwelli
Triceratium sp.
Biddulphia sinensis
B. granulata
Pennales
Licmophora sp.
Synedra sp.
Thalassionema bacillare
*T. nitzschoides**
*T. frauenfeldii**
T. longissima
Asterionella japonicus
Gyrosigma sp.
Pleurosigma sp.
P. elongatum
P. directum
P. normanii
P. delicatula
P. angulatum
Diploneis sp.
Navicula sp.
Navicula directum
Amphiprora sp
Amphora sp.
Cymbella sp.
Nitzschia sp.

N. closterium
N. longissima
N. seriata
Surirella sp.

Dinoflagellates (Pyrrophyceae)

Prorocentrum sp.
P. rostratum
Exuviella sp.
Dinophysis sp.
Amphisolenia sp.
Ornithocercus sp.
Gymnodinium sp.
Noctiluca miliaris
Ceratium sp.
C. bucephalum
C. furca
C. fuscus
C. lineatum
C. tripos
C. macroceros
Gonyaulax sp.
Oxytoxum scolopex
Pyrocystis sp.
Peridinium sp.
Podolampus sp.

Silicoflagellates

Dictyocha sp.

Coccolithophores

Coccolithus sp.
Rhabdosphaera sp.

Blue green algae (Cyanophyceae)

*Trichodesmium erythraeum**

Table . 1 - The list of phytoplankton species identified during different seasons in the western BoB. Designated dominant species in each taxonomic group are those with an asterisk.

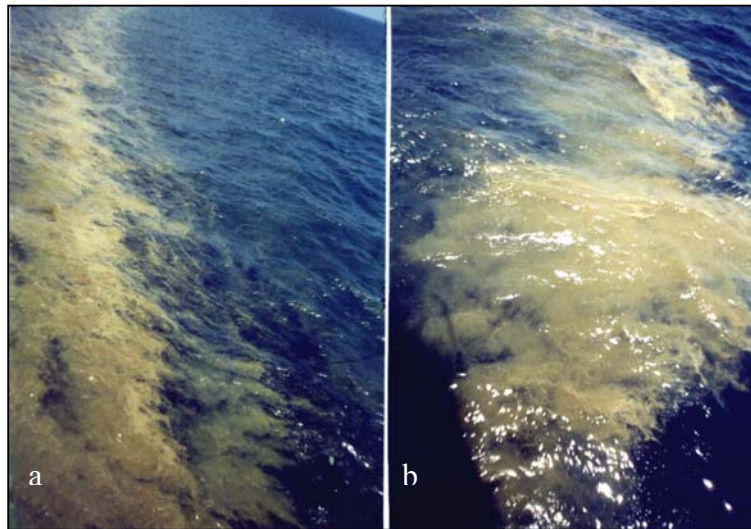


Plate 1 - Patches of *Trichodesmium erythraeum* bloom observed (a) off Karaikkal ($10^{\circ}58' N$; $81^{\circ}50'E$) and (b) off south of Calcutta ($19^{\circ} 44'N$; $89^{\circ} 04'E$) during spring intermonsoon period, c) microscopic view (20x) of *Trichodesmium erythraeum*

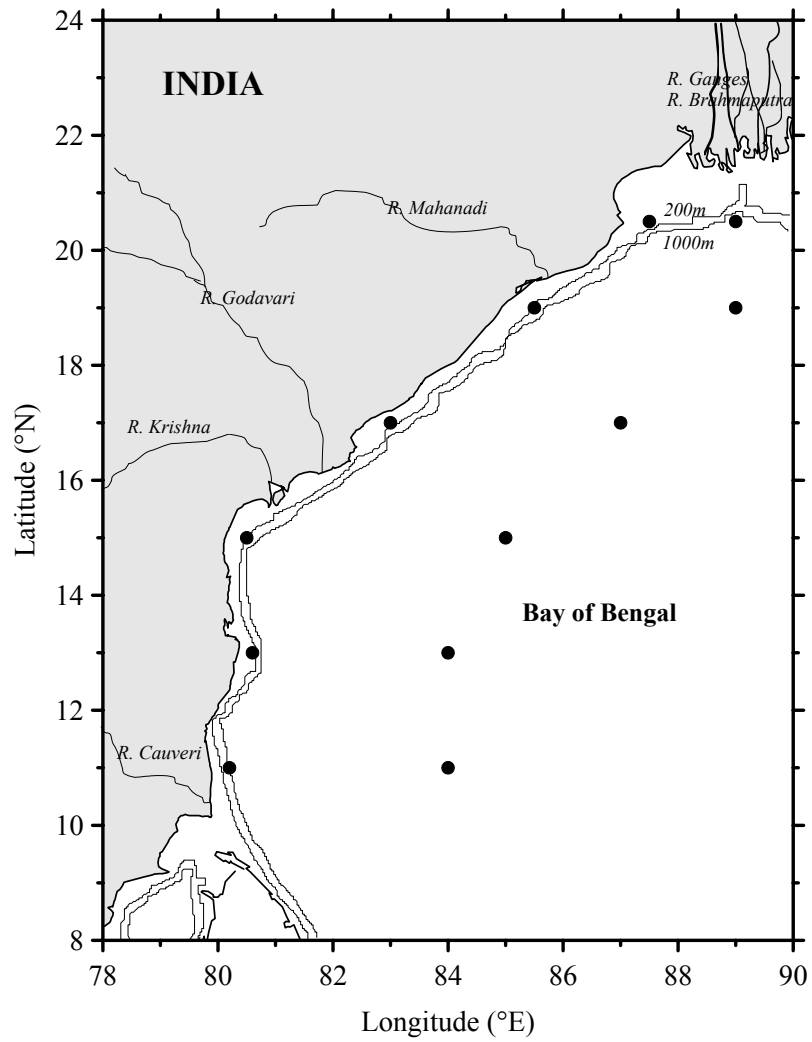


Figure. 1 - Map of the study area with station location

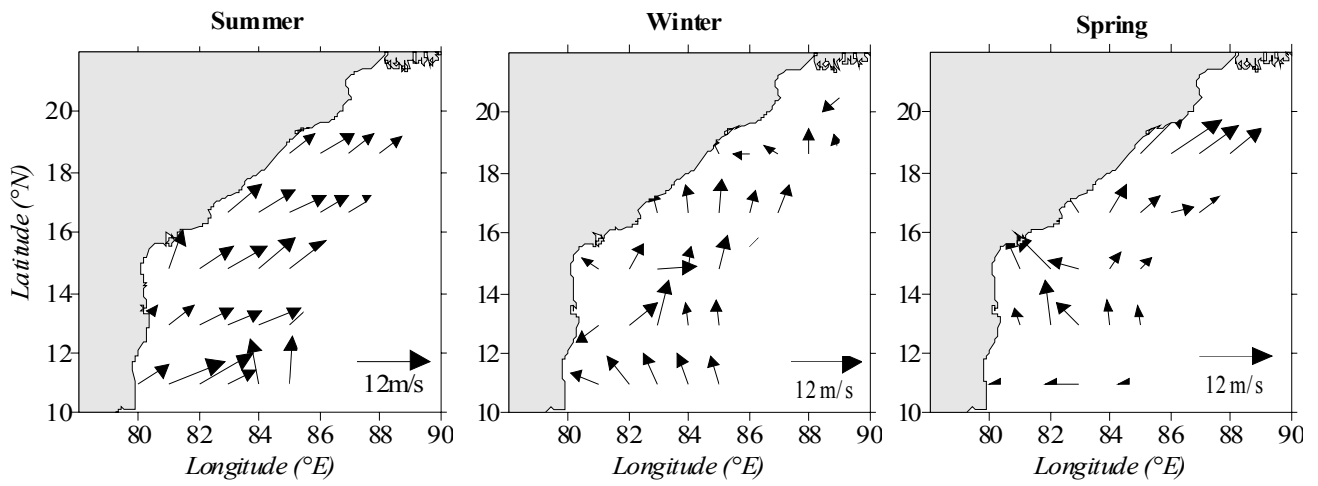


Figure. 2 – Direction and magnitude of wind in the western Bay of Bengal during three different seasons

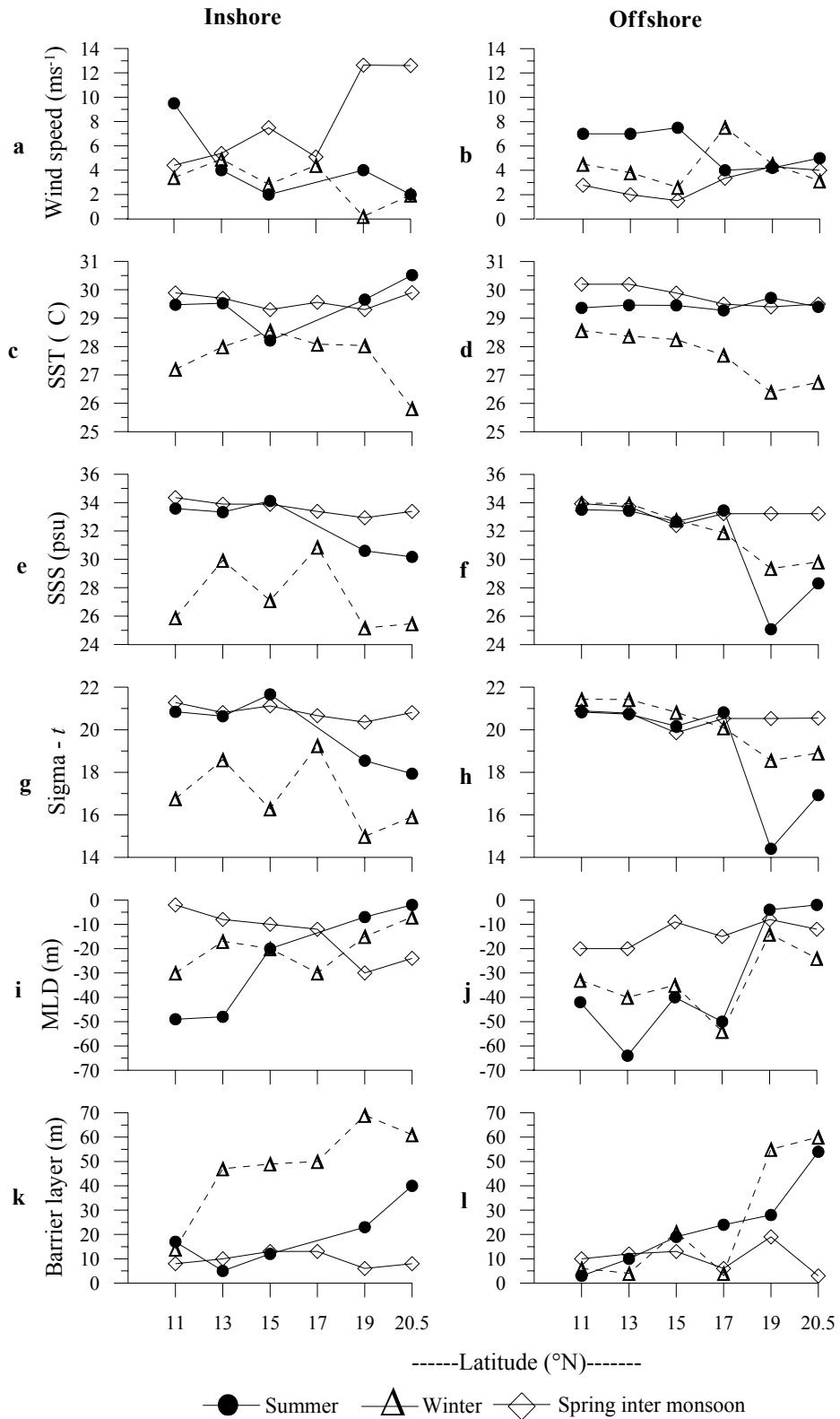


Figure. 3 - Distribution of wind speed (ms^{-1}), SST ($^{\circ}\text{C}$), SSS, Sigma- t , MLD (m) and barrier layer depth (m) along the inshore and offshore waters of western Bay of Bengal during summer, winter and spring intermonsoon periods

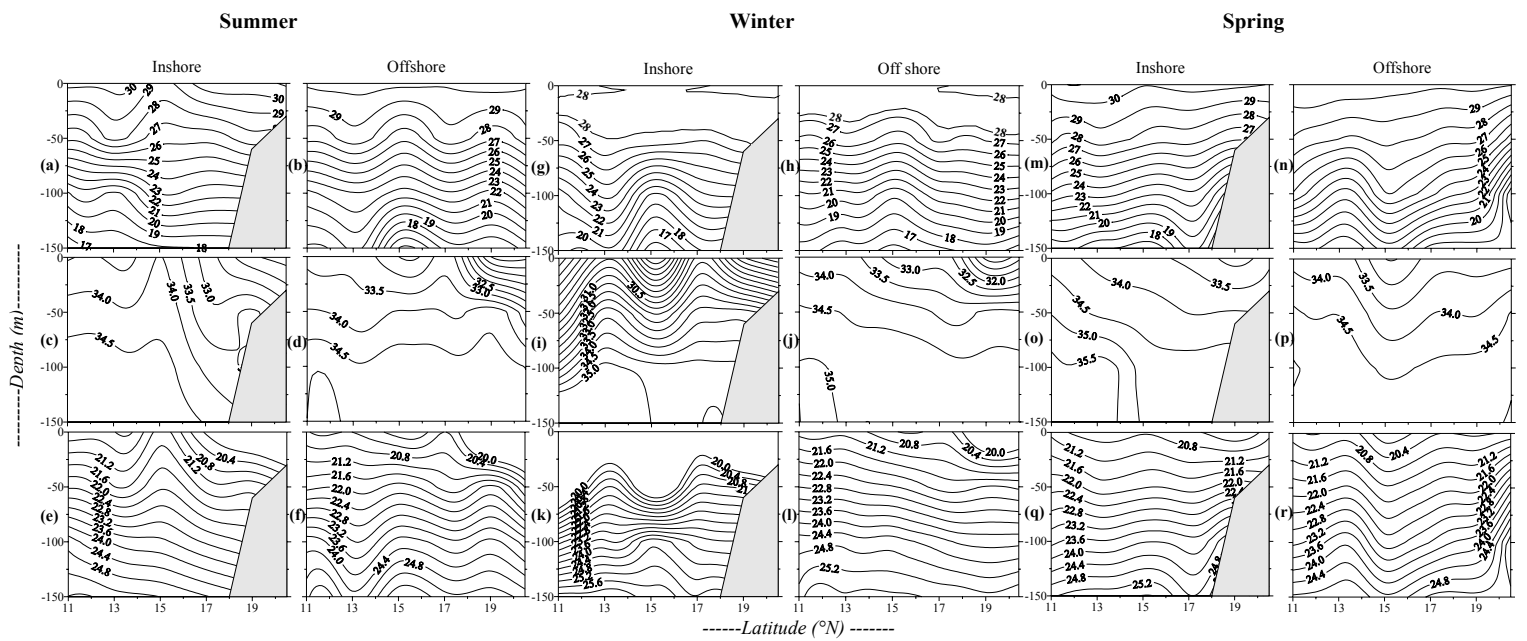


Figure. 4 - Vertical distribution of (a, b, g, h, m, & n) Temperature ($^{\circ}\text{C}$), (c, d, i, j, o & p) Salinity, and (e, f, k, l, q & r) Sigma - t upto 150m water column of inshore and offshore waters of western Bay of Bengal during summer, winter and spring inter monsoon seasons.

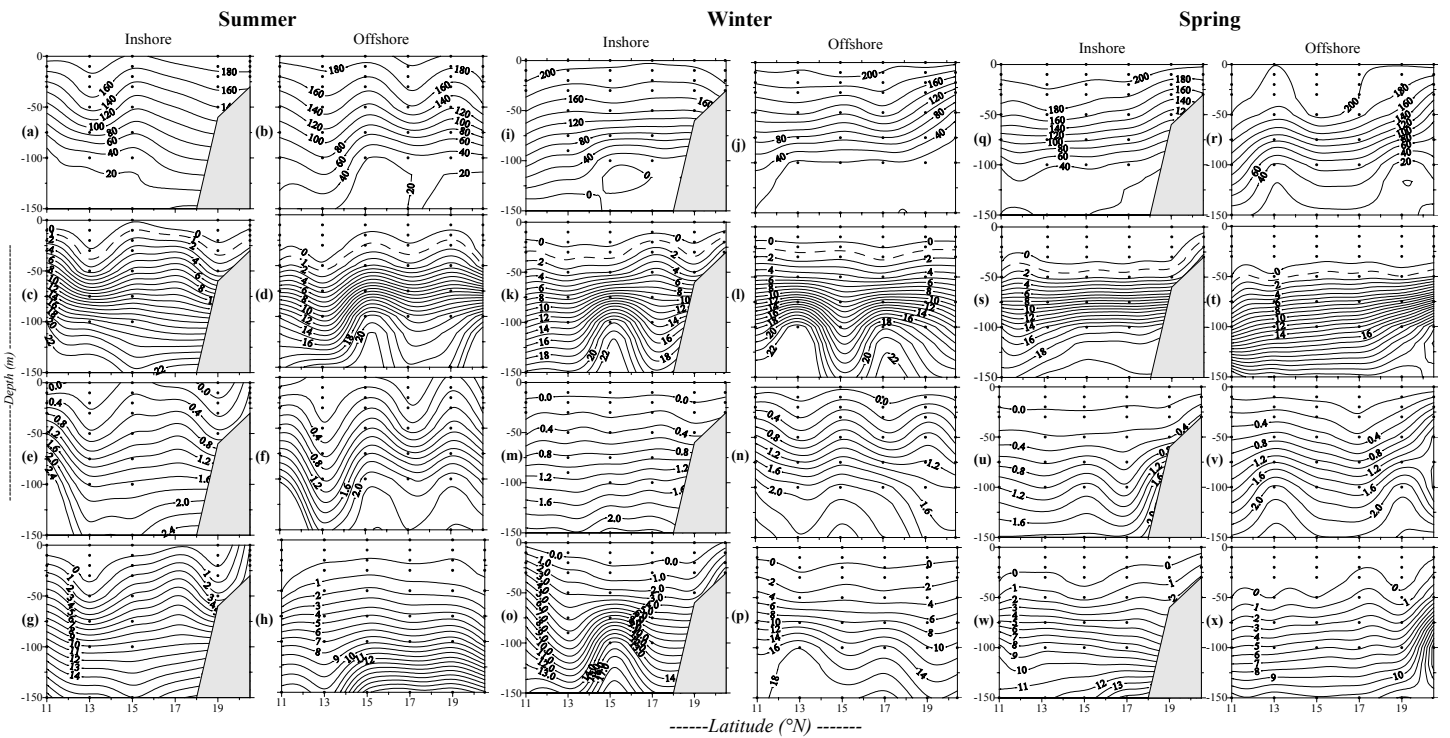


Figure 5 - Vertical distribution of (a, b, i, j, q & r) Dissolved oxygen (μM), (c, d, k, l, s & t) Nitrate (μM), (e, f, m, n, u & v) Phosphate (μM) & (g, h, o, p, w & x) Silicate (μM) 150m water column of inshore and offshore waters of western Bay of Bengal during summer, winter and spring inter monsoon seasons.

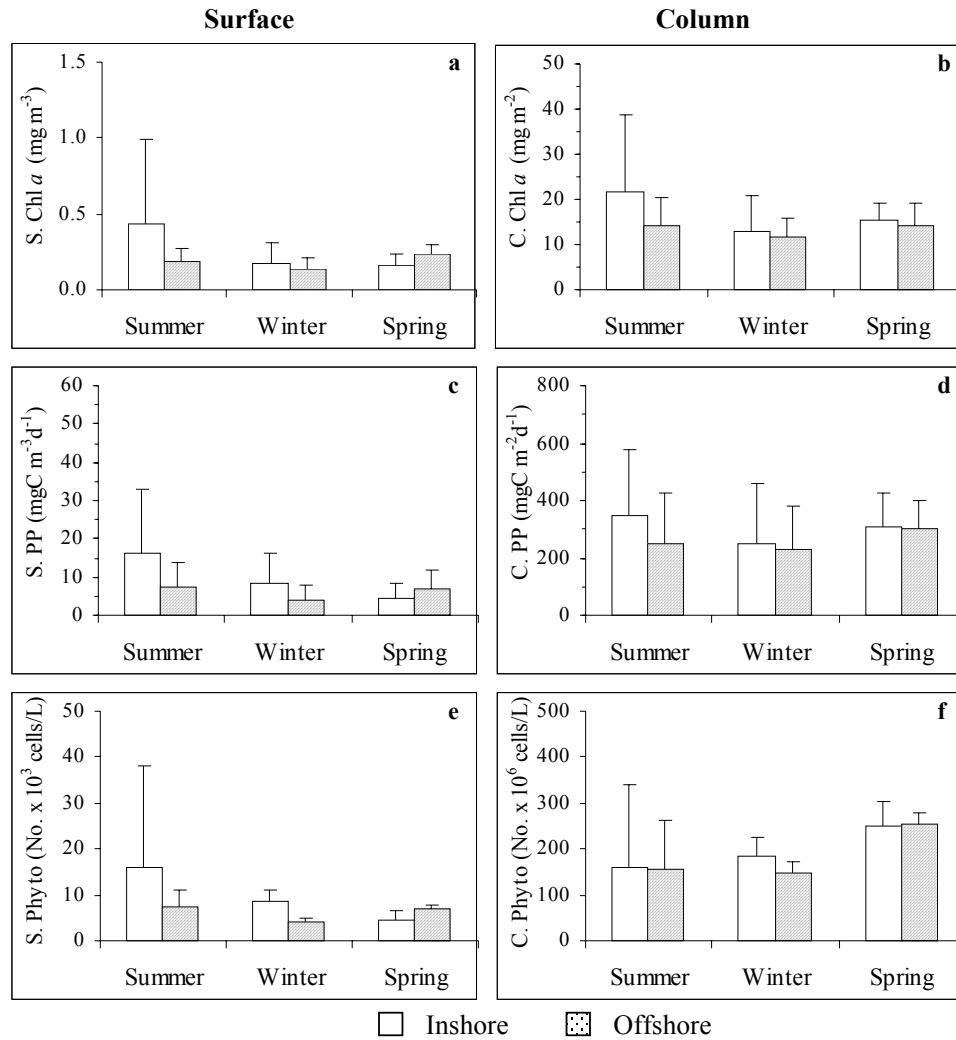


Figure . 6 - Distribution of average chlorophyll *a*, primary production and phytoplankton density (both surface and column) in the inshore/offshore waters of western Bay of Bengal during summer, winter and spring intermonsoon seasons

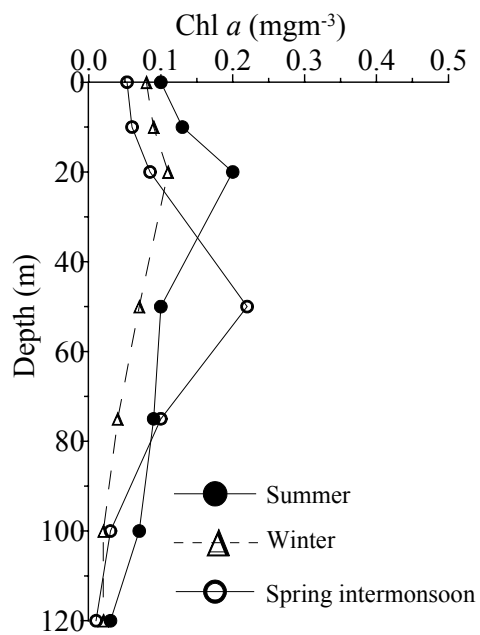


Figure. 7 - Seasonal trend in the vertical distribution of chlorophyll *a* (mgm⁻³) in the western Bay of Bengal during summer, winter and spring intermonsoon seasons.

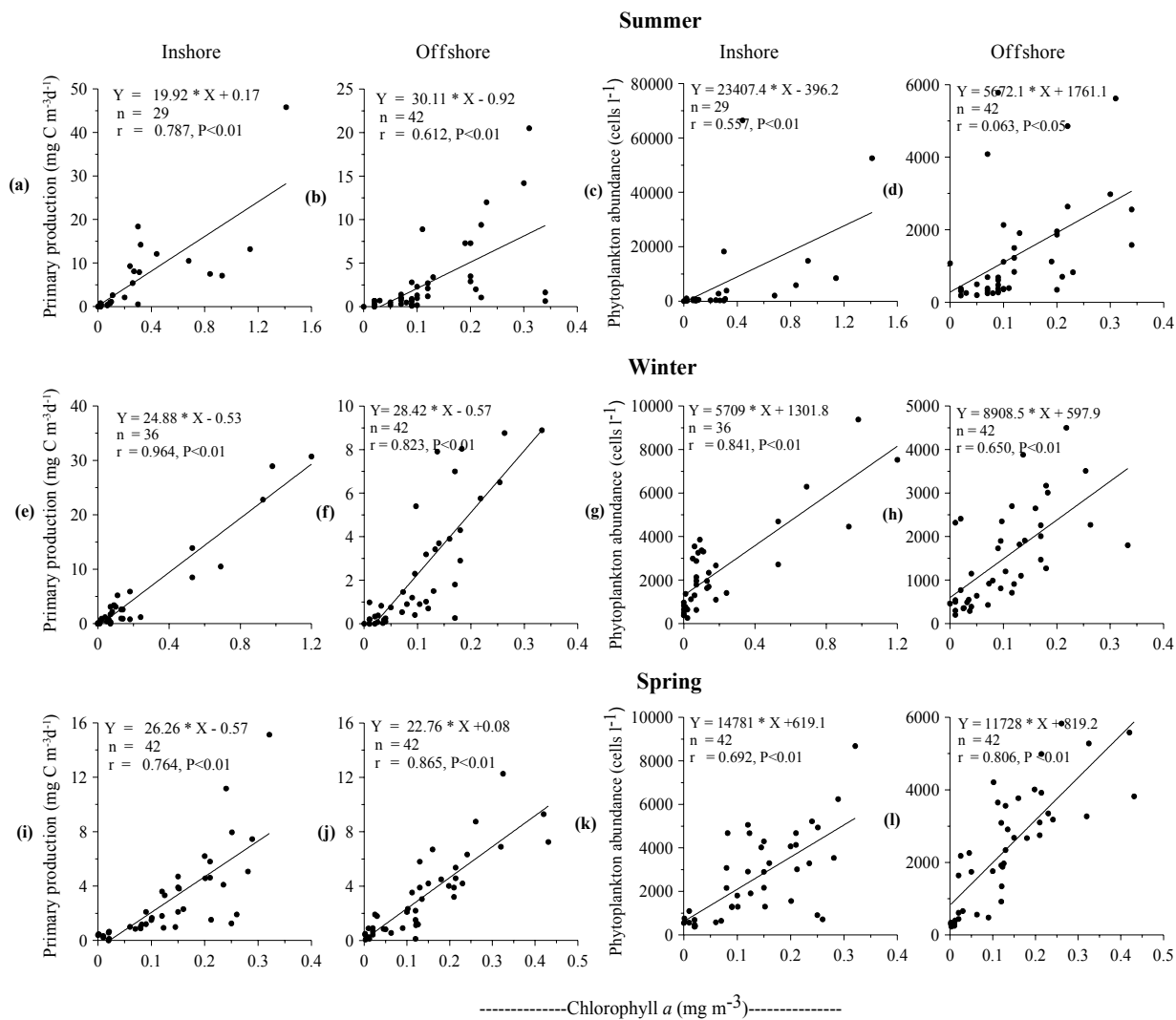


Figure. 8 - Linear correlation of chlorophyll a to primary production and phytoplankton density of inshore and offshore waters of the western Bay of Bengal during different seasons

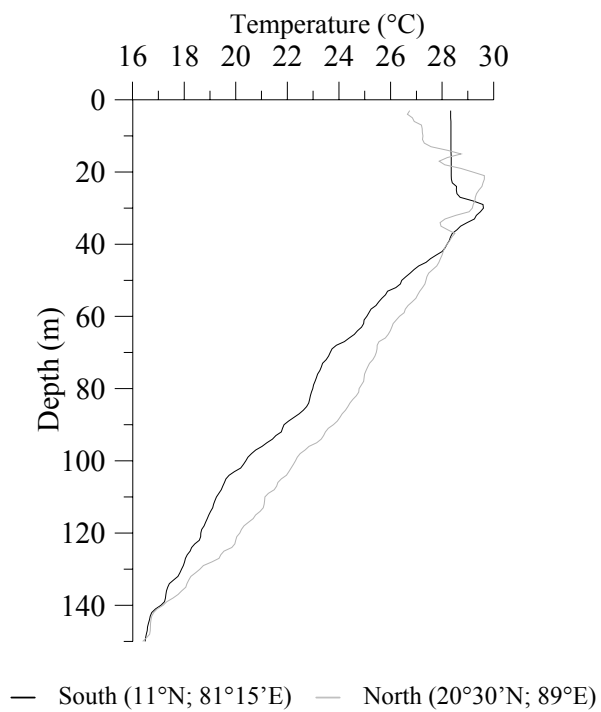


Figure. 7 – General trend in the vertical distribution of temperature (°C) in the western Bay of Bengal during winter monsoon season.

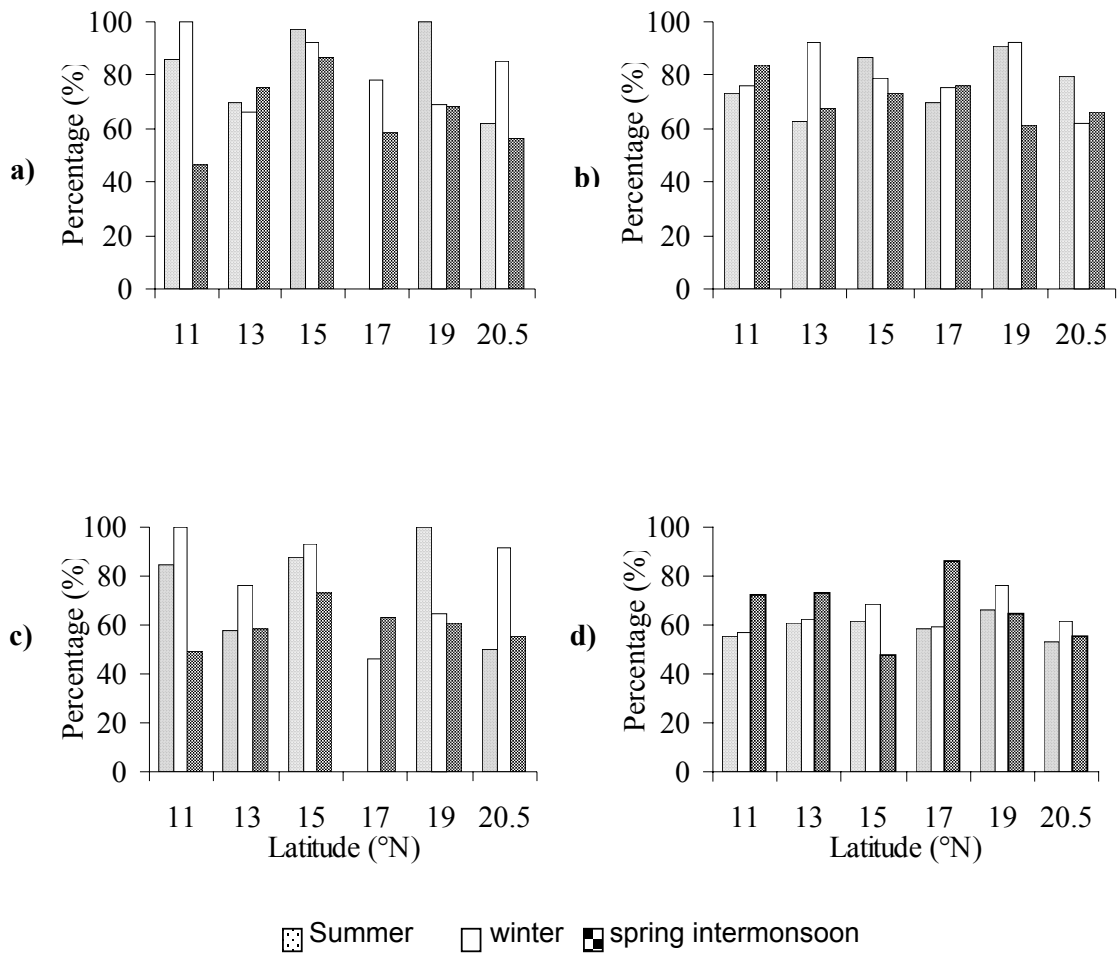


Figure. 10 - Percentage contribution of primary production (a & b) and chlorophyll a (c & d) in top 50m of the 0 -120m water column in inshore and offshore waters of western Bay of Bengal during summer, winter and spring intermonsoon.