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Oscillating environmental responses of the eastern Arabian Sea

Vijay John Gerson[1*], Madhu N V[2], Jyothibabu R[2], Balachandran K K[2],
Maheswari Nair[2] & Revichandran C[2]

[1]St.Albert's College, Mahatma Gandhi University, Kochi- 682018, India
[2]National Institute of Oceanography, Regional Centre, Kochi-682018, India
*[*][E-mail:vijay_kannilkal@yahoo.com]

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Characteristics of two distinct physical processes, the coastal upwelling and convective overturning, which enhance phytoplankton productivity in the west coast of India, are discussed in this study. Systematic *in-situ* data collected during the two contrasting monsoon (summer and winter) periods were utilized for the study. During summer monsoon, the colder (27°C), less oxygenated (<190 µM), nitrate rich (NO_3-N >2 µM) waters were evidenced in the upper layers of the southwest coast of India, along with higher level of primary production (surface - 76 mgC $m^{-3}d^{-1}$ & column - 1629 mgC $m^{-2}d^{-1}$) and chlorophyll *a* (surface - 1.2 mgm^{-3} & column - 45.7 mgm^{-2}). In contrast, during winter, the upper thermohaline layer of the northeastern Arabian Sea exhibited colder sea surface temperature (SST, 25-26°C), and deeper mixed layer depth (MLD, >70 m). This area was distinguished by less oxygenated (<180 µM), nitrate rich (>2 µM) and high productive (surface - >10 mgC $m^{-3}d^{-1}$ & column - >800 mgC m^{-2} d^{-1}) waters. I can be stated that the physically forced chemical changes occurred in the upper layers of both southeastern and northeastern Arabian Sea, appeared in an oscillating manner with respect to monsoonal changes, seemed to trigger the enhancement of phytoplankton productivity of the area.

[Keywords: Upwelling, Winter cooling, Nutrients, Chlorophyll a, Primary production]

Introduction

The eastern Arabian Sea (EAS), positioned along the western continental margin of the Indian subcontinent, experiences a time dependent wind stress during south-west monsoon (SM) season[1], creating coastal upwelling[2-4]. Normally the signatures of upwelling begin to appear in the southwest coast of India by the onset of summer monsoon, and seem to extend towards north gradually within a few weeks of time[5-6]. This physical phenomena eventually causes high biological production in the nearshore (depth <200 m) waters[7-8].

The Northern Indian Ocean is a dynamic region influenced by the seasonally reversing monsoonal wind pattern[9,7]. Surface cooling and convective processes during winter, injects nutrients to the surface waters of northeastern Arabian Sea and influence production process along this region[7,10,8]. An outstanding feature of northern Indian Ocean is the development of oxygen minimum layers in the subsurface waters[11]. The high rate of production of organic matter in the surface layers of northern Indian Ocean leads to an increase in oxygen utilization at intermediate depths[12]. Occurrences of secondary nitrite maxima are considered as the evidence of nitrate reduction in this region. Present study attempts to investigate the seasonal patterns and stratification of nutrients to evaluate its distribution and related biological responses along the west coast of India.

Materials and Methods

The study is based on the oceanographic data collected from the EAS during the winter (December 2000) and summer monsoon (June 2001) periods by the National Institute of Oceanography, Regional Centre, Kochi under the project 'Marine Research-Living Resources (MR-LR) Assessment' programme funded by Centre for Marine Living Resources & Ecology (CMLRE), Kochi. The sampling was carried out onboard *FORV Sagar Sampada*. Sampling locations were in 1° longitudinal grid and 2° latitudinal grid (Fig. 1). Surface meteorological parameters were collected from all stations. Sea Surface Temperature (SST) was measured using a bucket thermometer. A Sea Bird CTD was used to collect temperature-salinity profiles. Salinity values from CTD were corrected against Autosal (Guildline)

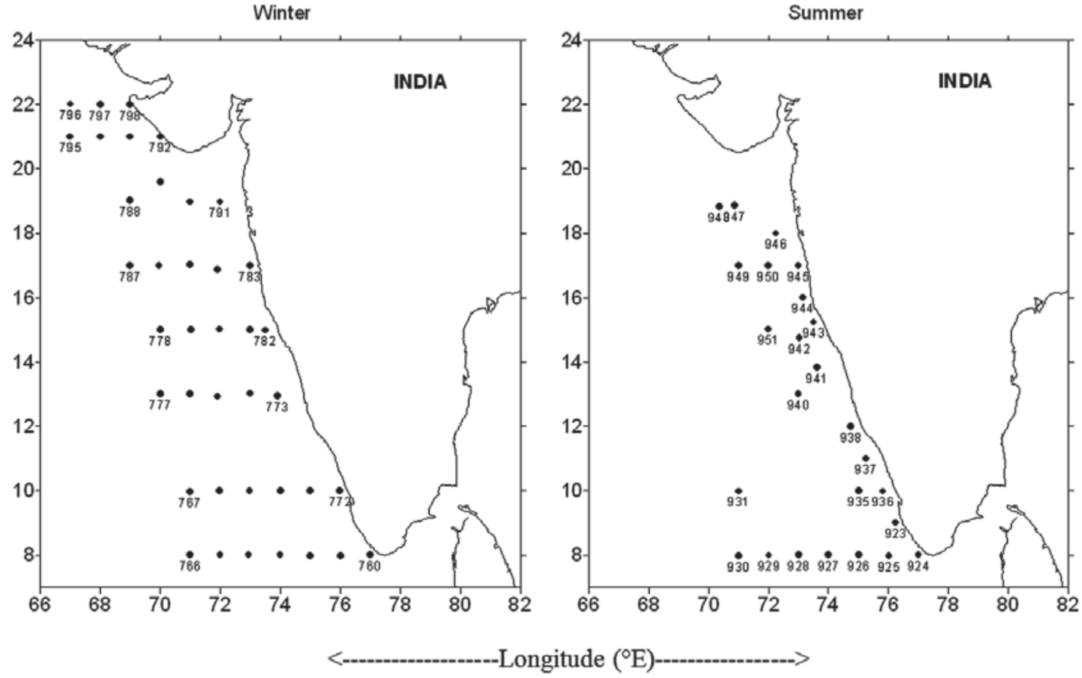

Fig. 1–Station locations during winter and summer

estimations. Water samples were collected from the predetermined depths, viz 0, 10, 20, 30, 50, 75, 100, 150, 200, 300, 500, 750 and 1000 m using CTD Rossette Sampler fitted with 1.8 litres Niskin bottles. Nutrients [Nitrate (NO_3^-), Nitrite (NO_2^-), Phosphate (PO_4^{3-}) and Silicate (SiO_4^{4-})] were analyzed immediately after the collection using SKALAR Segmented Flow Auto Analyzer[13]. Dissolved oxygen was estimated by the Winkler titration method. Water samples for estimations of chlorophyll *a* and primary production were collected from seven predetermined depths (0, 10, 20, 50, 75, 100 & 120 m) in the euphotic zone. Primary production was estimated by *in-situ* method using the C-technique[14]. For the estimation of chlorophyll *a*, one-litre seawater from each depth mentioned above were filtered through Whatman GF/F filters (nominal pore size 0:7 mm) and the absorbances of the extracted (using 90% acetone) pigments were measured using a Perkin-Elmer UV/Vis spectrophotometer[15].

Results

Summer monsoon

Hydrography and Chemistry

During this season, the average wind speed was about 8 m/s with appreciable variations. SST in the coastal station was 2.6°C lower than that of the farthest offshore station and the SST recorded a consistent decreasing trend from offshore to coastal region, which implies strong upwelling (Fig. 2a, b & c). Area between 8°N and 13°N & 77°E and 75°E was characterized by low SST (<28°C) and low MLD (~ 25 m) during this season (Figures 7b & d). Upsloping of isolines of temperature, salinity and density can be considered as strong signatures of coastal upwelling (Figures 2a-f). From the vertical distribution at 10°N (off Cochin), the subsurface isotherms above 80 m indicated gentle upsloping towards the coast, which implies upwelling effects yet to reach the surface (Figures 3d, 3e & 3f).

The vertical distribution of NO_3^- and SiO_4^{4-} revealed high concentrations at the surface layers along south west coast of India (Fig. 3). Horizontal distribution of NO_3^- at the depths of 0, 10, 20, 30 and 50 meters showed distinct spatial variation throughout the study area (Fig. 4). Upward shifting exhibited by the isolines of NO_3^- and SiO_4^{4-} along the 8°N & 10°N clearly indicated the upwelling signatures in the coastal waters (Figure 3). Nutrient rich waters (NO_3^- & SiO_4^{4-} > 2 µM) with comparatively low dissolved oxygen (<180 µM), observed west of 73°E, moves across the shelf and surfaces near the shore from at least about 60 m. At 20 m depth, the NO_3^- concentration varied between 1 µM in the offshore and 12 µM, near the coast over a distance of around 150 Km.

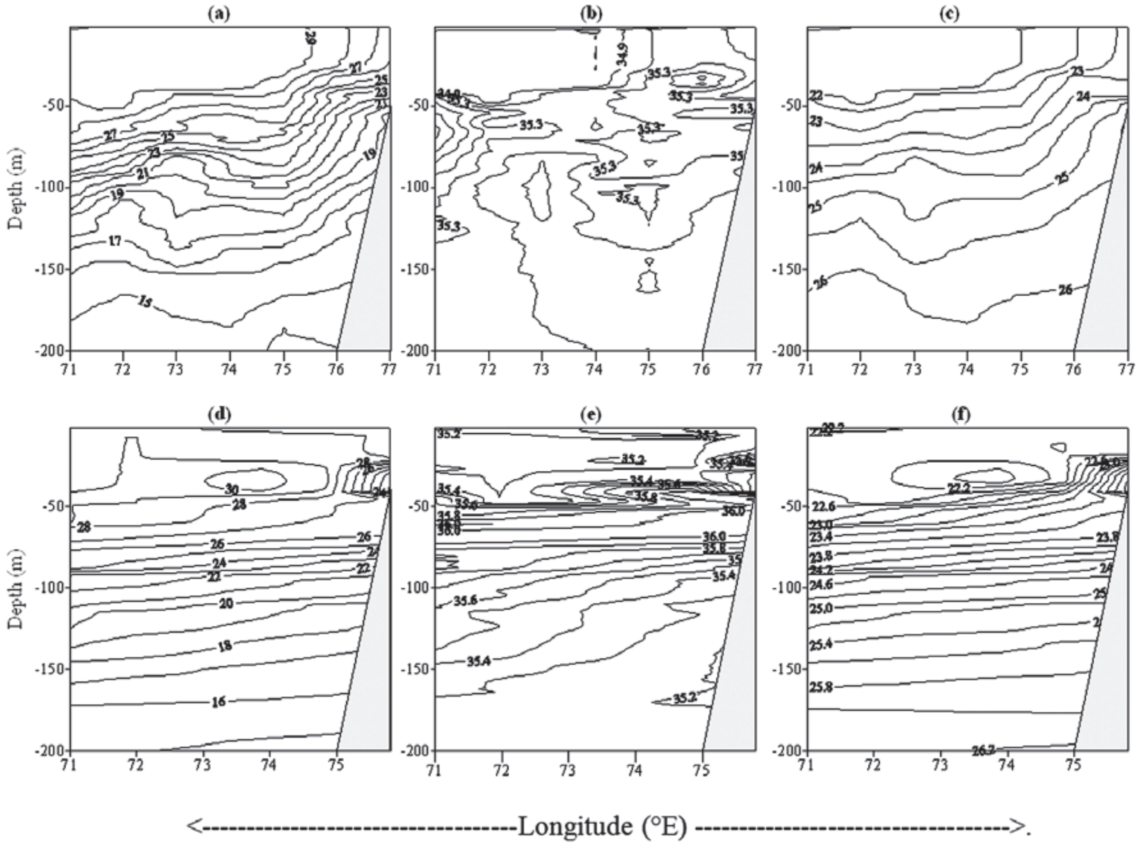

Fig. 2–Vertical distribution of temperature (°C), salinity and density along 8°N (a, b & c) and 10°N (d, e & f) during summer monsoon.

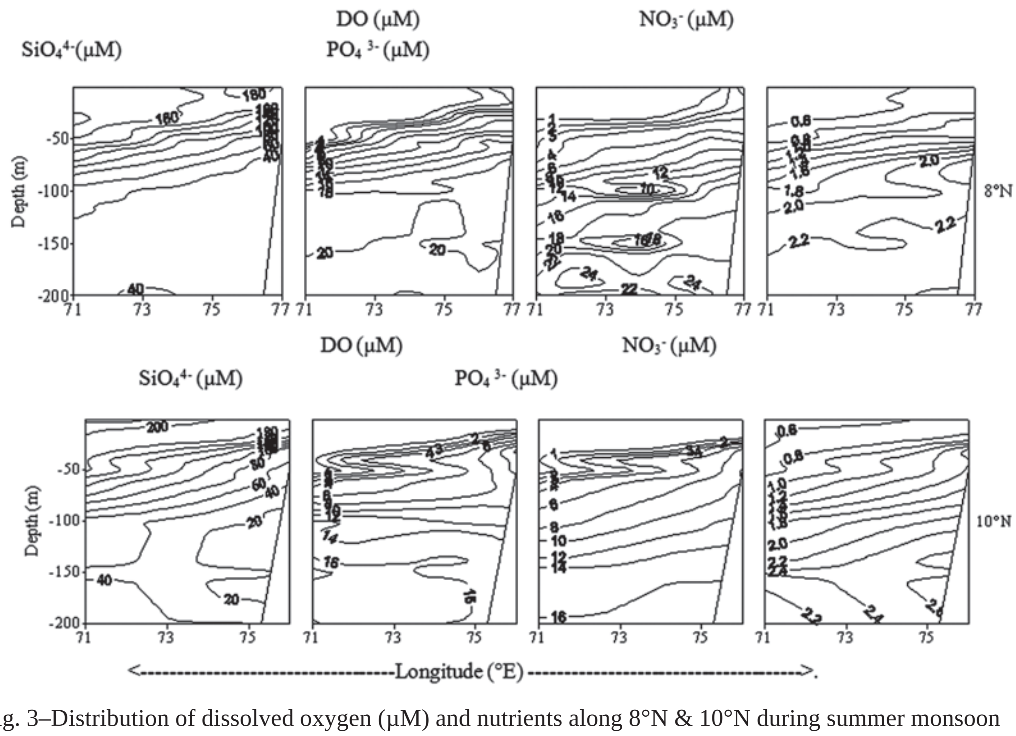

Fig. 3–Distribution of dissolved oxygen (µM) and nutrients along 8°N & 10°N during summer monsoon

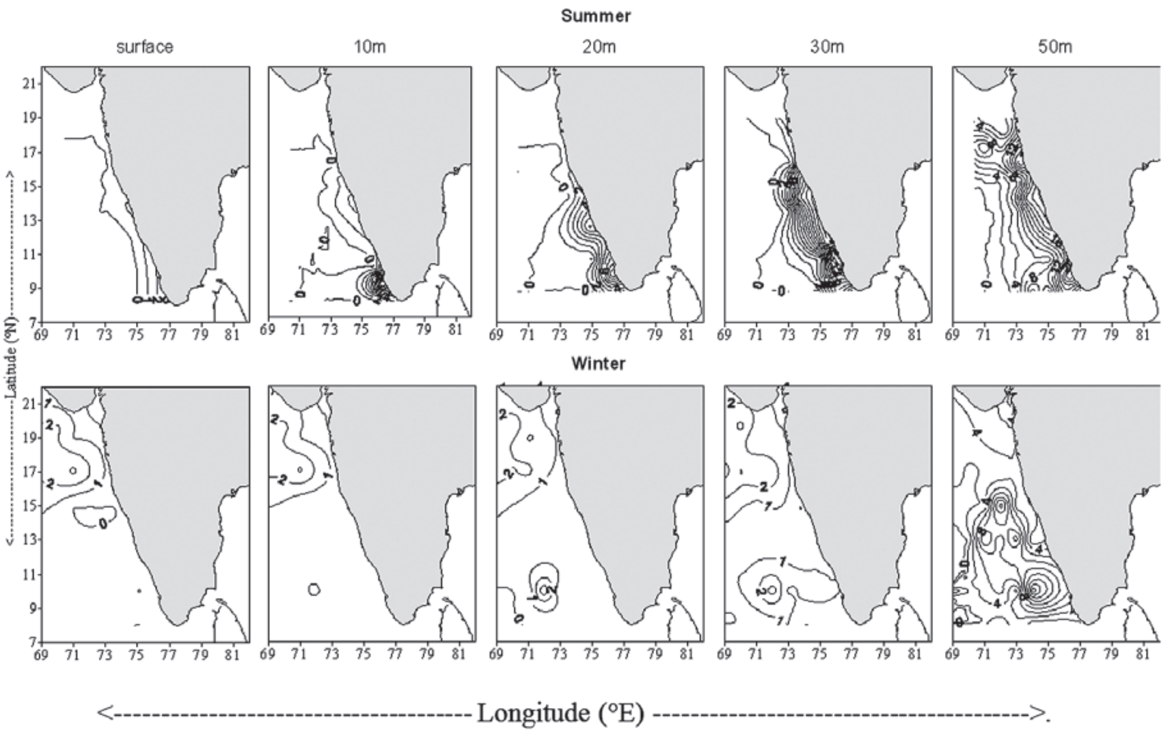

Fig. 4–Horizontal distribution of nitrate (µM) at different depths along the west coast of India during summer and winter

Chlorophyll a & Primary production

Relatively higher concentration of chlorophyll *a* was observed in the southwest coast of India during summer as compared to the northwest coast (Figure 5b & d). Concentration of chlorophyll *a* was ranged from 0.11 to 1.2 mg m^{-3} in the surface and 8.7 to 45.7 mg m^{-2} in the euphotic water column. Similar to chlorophyll *a*, primary production also showed relatively higher values in the southwest coast of India during summer as compared to the northwest coast (Fig. 5f & h). Primary production varied from 1.6 to 76 $mgCm^{-3}$ d^{-1} in the surface and 179 to 1629 $mgCm^{-2}$ in the euphotic column. At the coastal waters of 8°N, both chlorophyll *a* and primary production recorded maximum.

Winter monsoon

Hydrography and Chemistry

A drop of ~3°C in SST (25-26°C) was evidenced in the northwest region than that of the corresponding southwest (Fig. 6a & b). The upper thermohaline layers exhibited a sharp decrease in SST (<26°C) and deepening of MLD (>70 m) in the northeastern Arabian Sea. Vertical distribution of temperature showed a weak stratification of surface layers in the northeastern region AS as compared to the southwest,

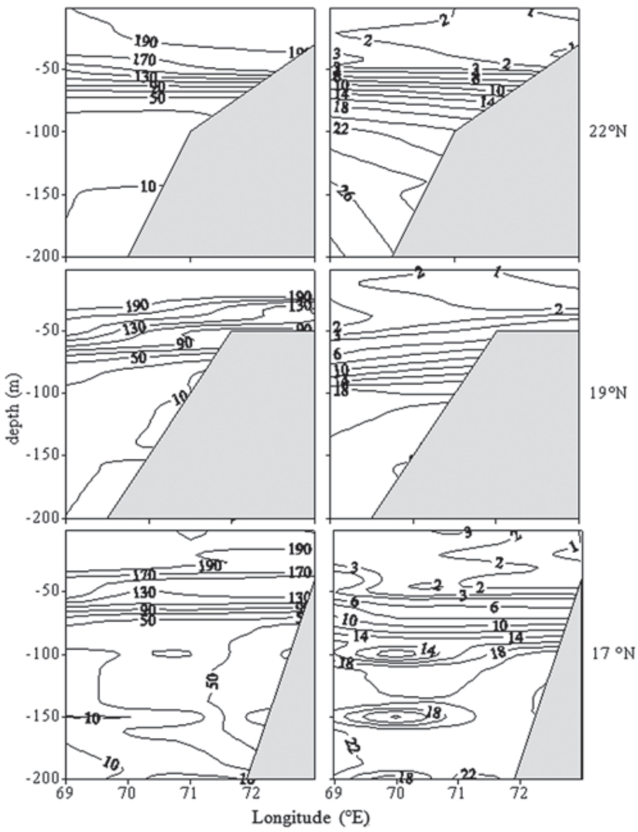

Fig. 5–Distribution of dissolved oxygen (µM) and nitrate (µM) along the northwest coast of India during winter

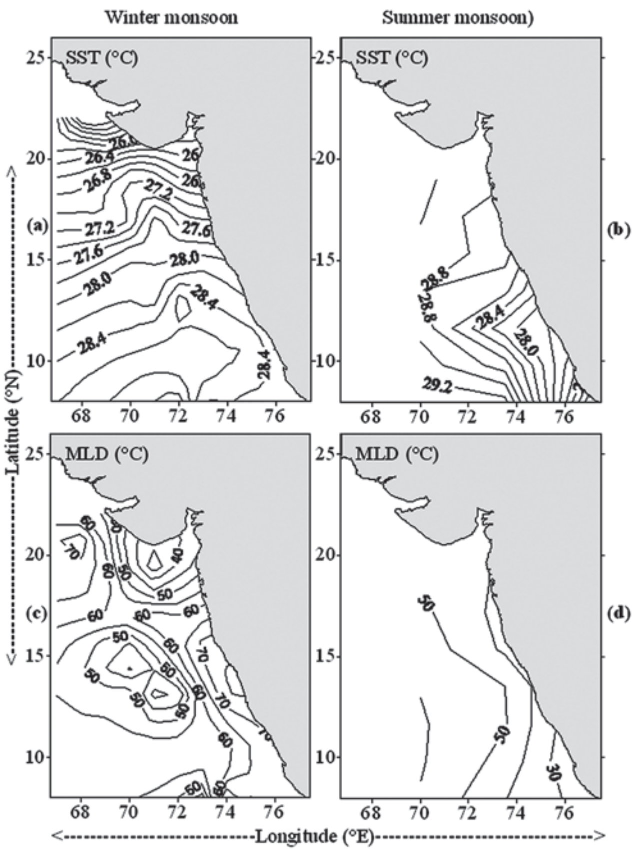

Fig. 6–Distribution SST (a & b) and MLD (c & d) along southwest coast of India during winter and summer

indicating the homogenous mixed layers (Figure 8a). Distribution of salinity in the surface layers exhibited a south to north increase (32-36.5).

Vertical distribution of DO, nitrate NO_3^- and NO_2^- were characterized by an oxygenated ; nutrient depleted surface layers in the southwest coast, whereas in the northwest region oxygenated, nitrate rich waters were evidenced (Fig. 7). In the northwest coast, nitracline (1µM) was located above 10 m depth,

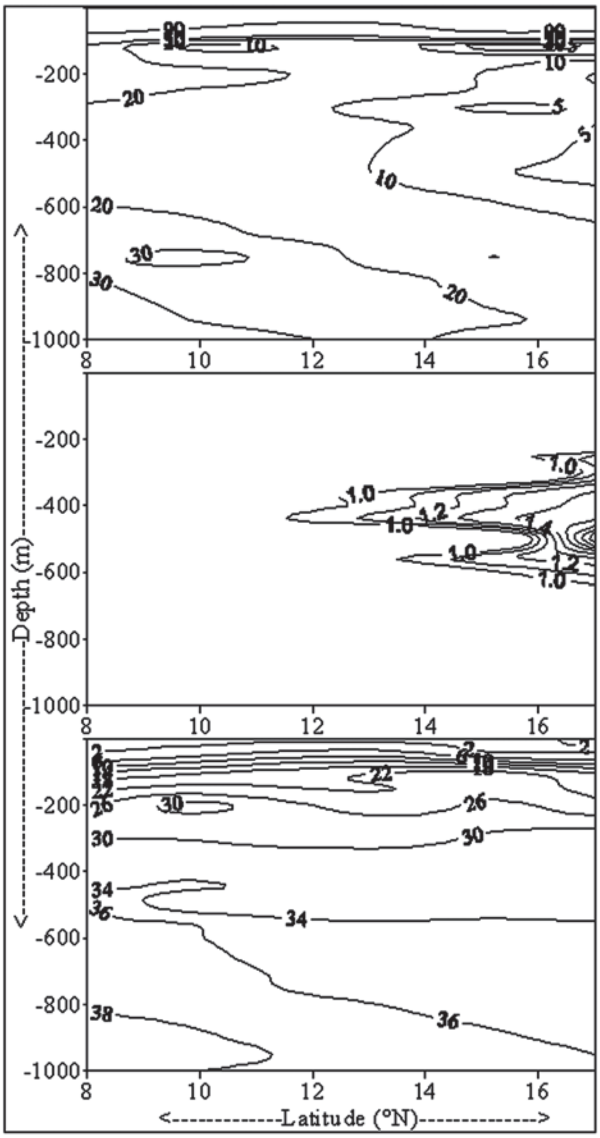

Fig. 7–Distribution of dissolved oxygen (µM), nitrate (µM) and nitrite (µM) along 71°E during winter

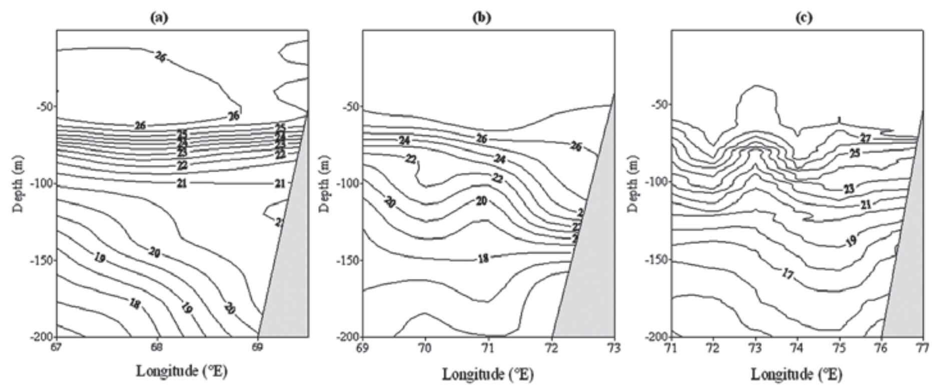

Fig. 8–Vertical distribution of temperature (°C) during winter monsoon along west coast of India (a) 21°N (b) 13°N and (C) 8°N Surface distribution of salinity along the west coast of India during winter monsoon.

whereas in the southwest coast, nitracline was evidenced in and below 50 m depth (Figs. 5 & 3).

Chlorophyll a & Primary production

In contrast to summer monsoon, chlorophyll *a* and primary production of both surface column waters were observed to be higher in the northwest coast as compared to the southwest (Fig. 10). Chlorophyll a concentration varied from 0.01 to 2.1 mg m^{-3} in the surface and 4.1 to 58 mg m^{-2} in the euphotic water column. Off Veraval (21°N & 70°E) showed maximum surface and column chlorophyll *a* (2.1 mg m^{-3} and 82.4 mg m^{-2}). Surface primary production was varied from 2 to 53.4 mg C m^{-3} d^{-1} in the surface and 105 to1854 mg C m^{-2} d^{-1} in the water column. Similar to chlorophyll *a*, maximum primary production was also observed in the coastal waters off Veraval.

Discussion

A lot of studies have been carried out in the EAS pertaining to the changes of hydrographic and biological properties induced by the seasonal reversals of monsoons[9,7,10,16]. Even though the eastern Arabian Sea is located in the western margin of Indian sub-continent, the oceanographic characteristics between the southern and northern region exhibits an entirely different scenario due to the influence of prevailing monsoons[7,8,17]. Present study discusses the variability in hydrographical and biological properties occurred in the upper water column of the eastern Arabian Sea during the two contrasting monsoon periods (summer and winter). During winter, the cold SST (<26°C), high salinity (36.5), deeper mixed layer

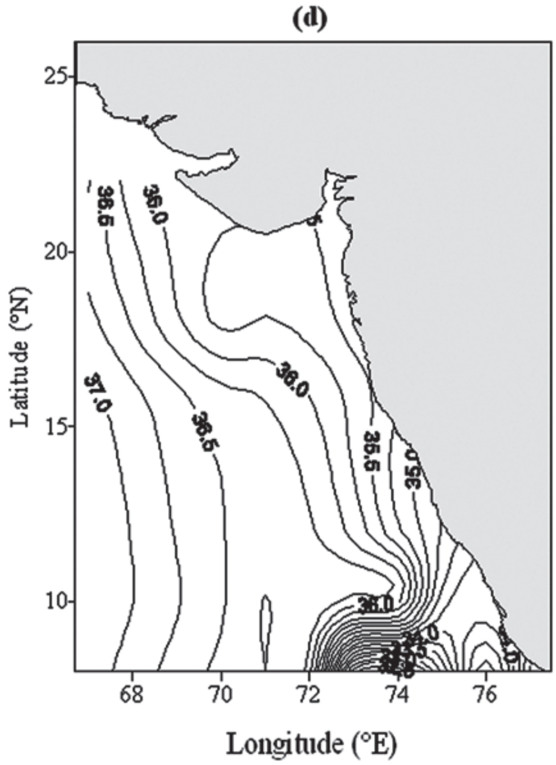

Fig. 8d–

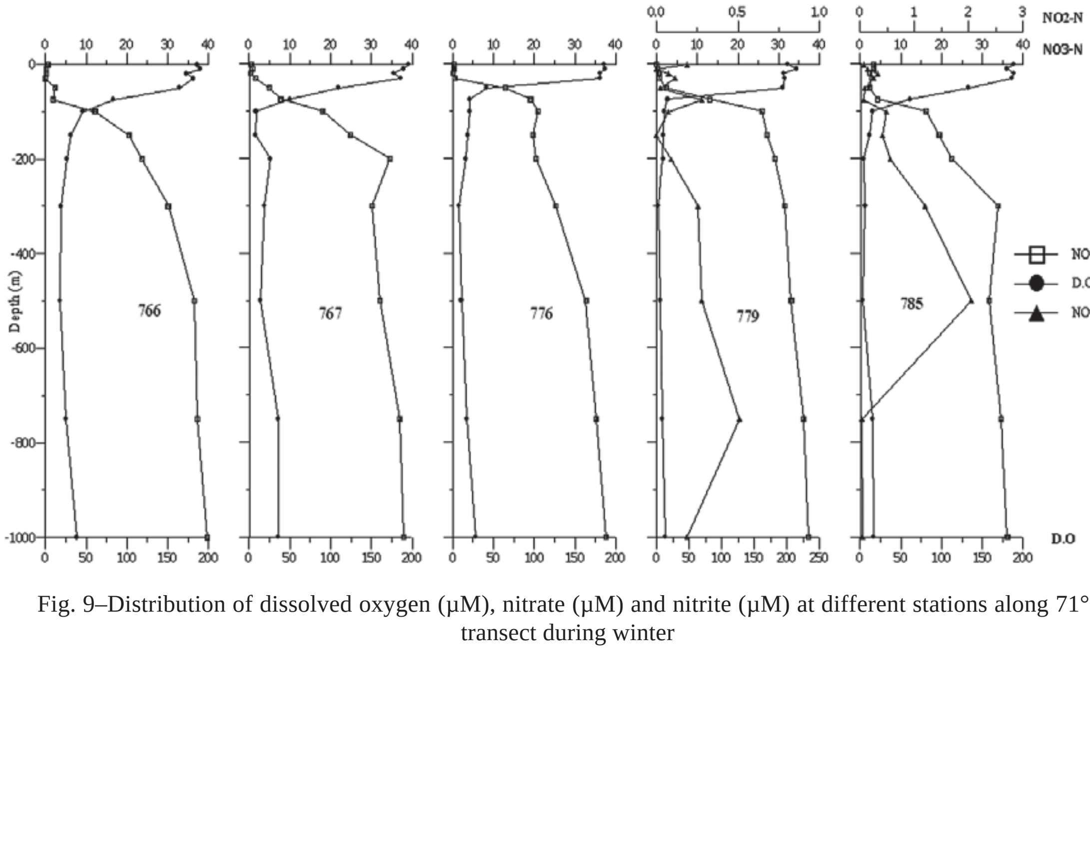

Fig. 9–Distribution of dissolved oxygen (μM), nitrate (μM) and nitrite (μM) at different stations along 71°E transect during winter

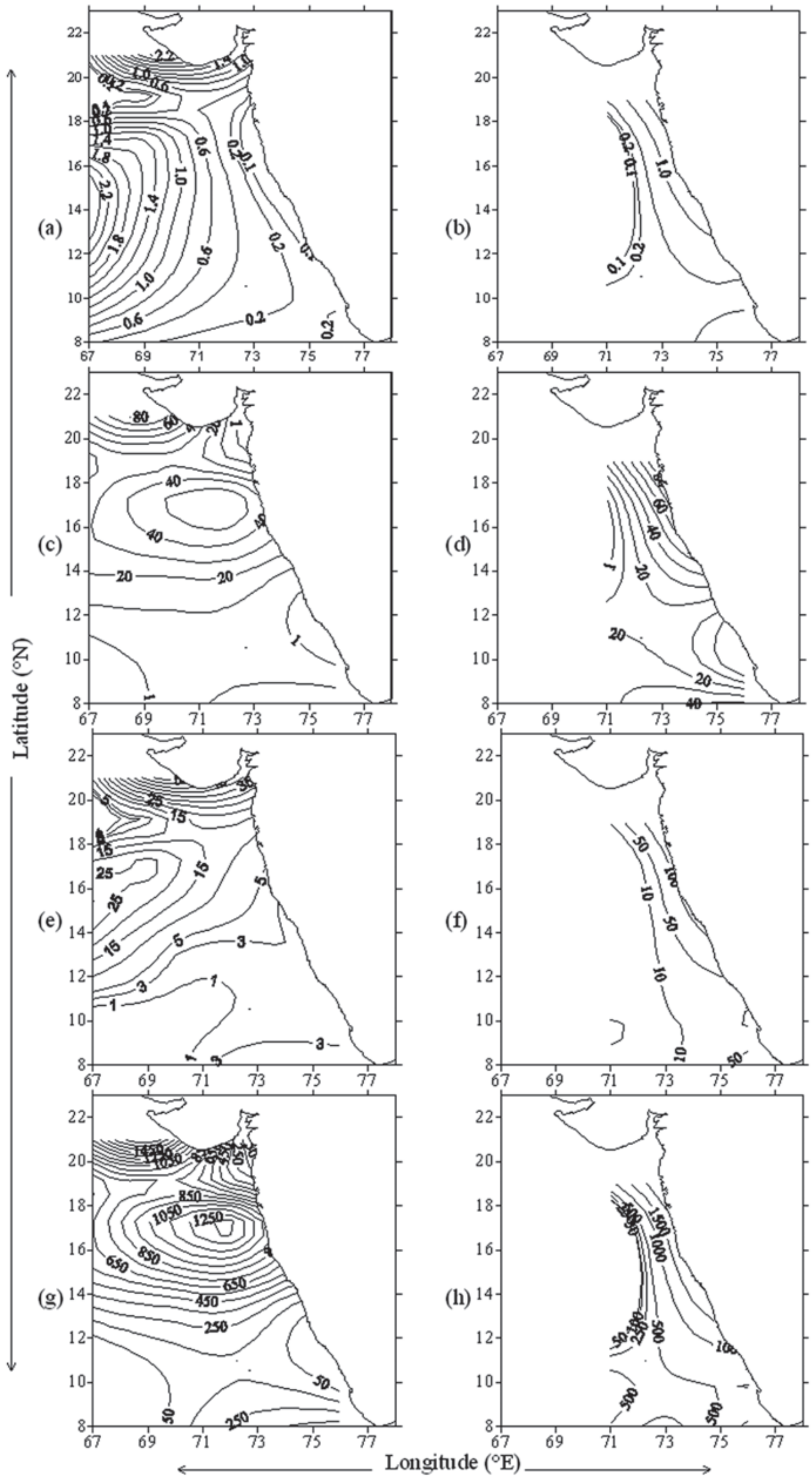

Fig. 10–Distribution of (a & b) surface chlorophyll *a* (mg m^{-3}), (c & d) column chlorophyll *a* (mg m^{-2}), (e & f) surface primary production (mgC $m^{-3}d^{-1}$), (g & h) column primary production (mgC $m^{-2}d^{-1}$) during winter monsoon and summer monsoon.

(>70 m) prevalent in the northeastern Arabian Sea indicates the process of winter convective mixing. A Shallow nitracline and low DO observed in the surface waters substantiates the process of winter convection during this period. Depletion of nutrients in the mixed layer was folowed by a relatively high chlorophyll *a* and primary production along the northern latitudes especially 21°N during winter, while southern latitudes, chlorophyll *a* and primary production were low (Figs. 5c & 5g). The upwelling enhances the chlorophyll *a* and primary production in the southwest coast of India during southwest monsoon much higher than in the northwest coast (42.3 mg m^{-2} & 1120 mg C m^{-2} d^{-1}). Distribution of dissolved oxygen and nutrients clearly reveals the northward increase in the magnitude of convective mixing. In northern Indian Ocean oxygen is severely depleted at the intermediate depths. DO concentration between 150-1000 m was observed to be less than 10 µM along a large part of the northwest coast of India, generating severe mid depth oxygen deficiency in the northern Indian Ocean. This zone is characterized by intense denitrification. Distribution of nitrate at intermediate depths of the northern region during winter portraits a comparable reduction[18,12]. This reduction resulted by the drastic consumption of dissolved oxygen by the sinking organic matter, loading to a secondary nitrite maxima at the intermediate depths along the northern region (Fig. 9). The strong density gradient and poor horizontal advection due to the semi-enclosed nature of the northern Indian Ocean, tends to restrict the supply of oxygen to the waters below the euphotic zone[11]. DO was saturated is the surface layers and decreased with depth to less than 5 µM, at intermediate depths along northern latitudes (Fig. 9). During the pre-monsoon (summer) season, Arabian Sea surface waters (up to ~30 m) are characterized by saturated dissolved oxygen (>200 µM) and depleted in nutrients, which increase below thermocline[19]. Thermal stratification bring a barrier to vertical nutrient flux are therefore not readily available to the euphotic zone[20]. Atmospheric forcing changes the upper layer of the northern Arabian Sea is a combination of enhanced evaporation and reduction in solar insolation. Subsequent cooling and convective mixing injects nutrients into the surface layers which in turn triggers the primary production[21]. It can be presumed that maximum vertical convection of surface layers takes place after the surface warming has tapered and winter mixing is well underway. Upwelling is not only associated with local winds, but also with the more large scale monsoonal condition which drives the anticyclonic Arabian Sea monsoon gyre[22].

Conclusion

Upwelling is characterized by low sea surface temperature and high nutrients in the upper ocean, which begin to appear when the monsoonal trade winds become active from the month of May onwards and slowly propagate northwards intensify along west coast of India during June to August[23]. However the upwelling along the west coast of India is mainly restricted to the southwestern coast. The concentration of nutrients east of 75°E were high in the south west coast. This is particularly evident in the distribution of NO_3^- at 30>6µm the south west coast. (Fig. 4) the upwelled waters could be traced north of 15°N as the physical forces triggering the upwelling weak. Distribution of that NO_3^- in the southwest tip of India endorse, the upwelled waters are not advected far whom shore. Westward displacement of the surface waters from the eastern Arabian Sea, during summer is restricted to the southwest coast of India[24]. To conclude the manifold climatic changes fall in annually impart an oscillating environmental nature to the eastern Arabian Sea.

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