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Variabilities in the community structure of phytoplankton in the upwelled and non-upwelled waters of southeastern Arabian Sea during the early summer monsoon

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The community structure of microphytoplankton was assessed along the southeastern Arabian Sea during the early phase of the summer monsoon. The study records an intense coastal upwelling along the southernmost region (off Thiruvananthapuram), which decreased further north. High chlorophyll-*a* (10.8 mg m^{-3}) and nutrient concentration was recorded in the coastal waters of Thiruvananthapuram. Even though off Mangalore (12° N) and off Goa (15° N) where upwelling was confined to narrow coastal zone, also showed high chlorophyll-*a* concentration, 3.98 mg m^{-3} and 6.31 mg m^{-3}, respectively. The upwelled waters were dominated by centric diatoms (*Thalassiosira* sp.) and the non-upwelled waters (12° N and 15° N) were dominated by dinoflagellates. Microphytoplankton cell density was the highest along off Thiruvananthapuram (4.8×10^4 cells L^{-1}), with maximum cell density along the coastal waters (1.4×10^4 cells L^{-1}). Phytoplankton community of upwelled and non-upwelled waters showed significant variations with 60 % similarity between phytoplankton communities of upwelled waters.

[**Keywords**: Diatoms, Microphytoplankton, South Eastern Arabian Sea, Summer monsoon, Upwelling]

Introduction

The South Eastern Arabian Sea (SEAS) is one of the worlds most productive region, facing an intense coastal upwelling during the summer monsoon period. The summer monsoon upwelling is said to increase the phytoplankton production along the SEAS[1]. This physical process is said to directly or indirectly influence the community and the trophic structure of phytoplankton. The changes observed in the phytoplankton community during this period is mainly due to the temporal variations occurring within the physico-chemical factors such as temperature, illumination, turbidity and nutrients, that are associated with the progression of the upwelling process[2-5]. Usually, the chain-forming diatoms with fast and explosive growth dominated the upwelled waters, whereas more stable-stratified waters with weak upwelling favoured solitary diatoms and dinoflagellates[6-7]. Certain studies have reported the dominance of diatoms of the genera *Chaetoceros*, *Thalassiosira* and *Rhizosolenia* in the upwelling areas off northwest Africa[8]. The effect of upwelling on the diatom dynamics in an estuarine system influenced by coastal upwelling was studied by Tilstone *et al*.[9], where the physical processes were observed to have a major impact on the diatom dynamics than the biogeochemical processes initiated during the period. Hence in a coastal ecosystem, upwelling could be considered as a main driving force structuring the phytoplankton community composition. Subrahmanyan[10] reported a seasonality in the composition of phytoplankton along the SEAS, with the maximum abundance observed during the southwest monsoon period. Other than this an intense variations in chlorophyll pattern was also observed during this period[1,11-14].

With the onset of the summer monsoon (May-June)[15], upwelling starts along the the south-west coast of India and with the progression of summer monsoon it propagates towards the north and persisted till October[16]. Upwelling arising along the southern tip of the Indian peninsula (Cape Comorin) is strong and wind-driven[17]. According to Habeebrehman *et al*.[14], the changes occurring within the intensity of the upwelling events could result in alterations in the biological responses. Thus, the present study attempts to provide an account on the community composition of phytoplankton and physico-chemical conditions of the south eastern Arabian Sea during the early phase of the summer monsoon, focusing mainly on the influence of upwelling on the community structure of microphytoplankton.

Materials and Methods

The study was conducted along the coastal and open ocean regions of the southeastern Arabian Sea during the early phase of the summer monsoon on-board FORV Sagar Sampada. Five latitudinal transects, namely, off Thiruvananthapuram, off Kochi, off Calicut, off Mangalore and off Goa, were selected. Each transects had three stations based on the depth that included 30 and 50 m depths as the coastal station, 200 m depth as shelf station and 1000 and 2000 m depths as open ocean station (Fig. 1).

Vertical profiling of physico-chemical parameters (temperature, salinity, dissolved oxygen and density) was done using CTD (Seabird 911 plus). Water samples from standard depths (0, 10, 20, 30, 50, 100 and 120 m) were collected using the rosette system equipped with Niskin bottles, attached to the CTD profiler. Chlorophyll-*a* concentration was estimated spectrophotometrically using a Hitachi U-2900 UV/Visible spectrophotometer following 90 % acetone extraction[18]. Major nutrients such as nitrate, phosphate, and silicate were analysed spectrophotometrically following the method of Grasshoff *et al.*[19]. Phytoplankton samples were collected by filtering ~ 50 liters of the surface waters through 20 µ bolting silk and the concentrate was preserved in 3 % neutralized formaldehyde solution. Qualitative and quantitative analysis of phytoplankton samples were carried out using a Sedgewick Rafter counting cell under a Leica DM2500 microscope following standard identification keys[20]. Statistical analysis was carried out using PRIMER V.6.

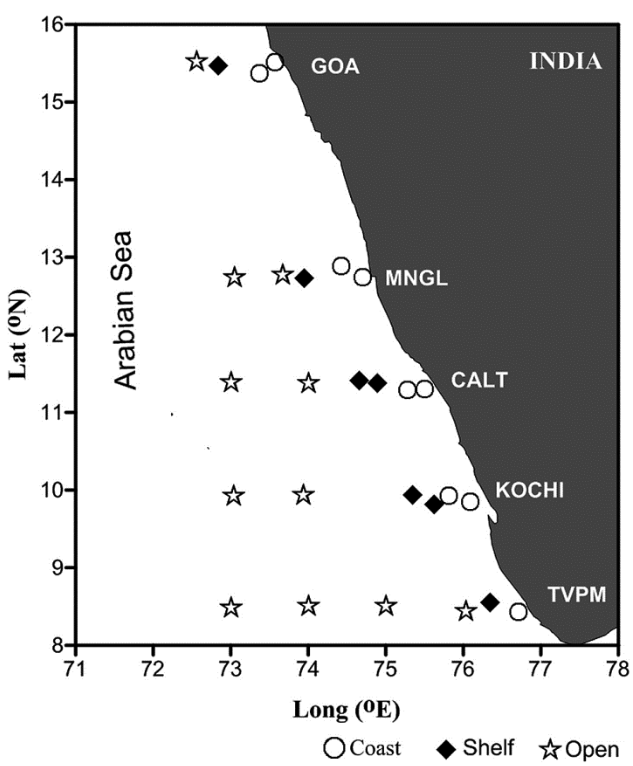

Fig. 1 — Study area - Southeastern Arabian Sea. Symbols (O) denotes coastal station, (♦) denotes shelf stations and (☆) denotes open water station locations

Results

Physico-chemical parameters

During the study period, upsloping of 24 °C isotherm was observed from 75 m to surface in the coastal waters of Thiruvananthapuram, indicating intense upwelling along the coastal waters, which extended towards the shelf and open ocean waters. A lower Sea Surface Temperature (SST) was observed in coastal waters (24.5 °C), which increased towards the offshore waters (28.6 °C). In the case off Kochi upsloping of 24 °C isotherm occurred from 75 m in the open ocean waters to sub-surface (20 m) in the coastal waters indicating upwelling in nearshore and shelf waters. Coastal SST was 26.6 °C which reached 28 °C in the offshore waters. In Calicut, the isotherm of 24 °C occupied > 70 m depth, thus indicating upwelling to the surface in the coastal waters. Here also, low SST was recorded in coastal waters (25 °C), which increased towards the offshore waters. Further north in Mangalore 24 °C isotherm was confined to a depth below 25 m, and in Goa upsloping of isotherm was not significant. Here the SST remained the same in coastal and offshore waters (28 °C; Fig. 2).

Generally surface nitrate, phosphate and silicate concentration were maximum along the coastal waters (3.1±0.49 µmol L^{-1}; 1.46±1.2 µmol L^{-1}; 14.29±9.3 µmol L^{-1}) which decreased towards the open ocean waters (2.4±0.23 µmol L^{-1}; 0.6±0.7 µmol L^{-1}; 3.52±2.4 µmol L^{-1}). In addition to this, it was observed that the upwelled waters of southern transects exhibited higher surface nitrate, phosphate and silicate concentration (2.88 – 3.25 µmol L^{-1}; 0.4 – 3 µmol L^{-1}; 9.33 – 20.6 µmol L^{-1}) as compared to the non-upwelled northern transects (1.9 – 2.5 µmol L^{-1}; 0.03 – 0.47 µmol L^{-1}; 0.96 – 7.15 µmol L^{-1}).

Chlorophyll-*a* distribution and phytoplankton community structure

Thiruvananthapuram transect

The average surface chlorophyll-*a* concentration along Thiruvananthapuram was 2.87±5.3 mg m^{-3}. High chlorophyll-*a* concentration was found in

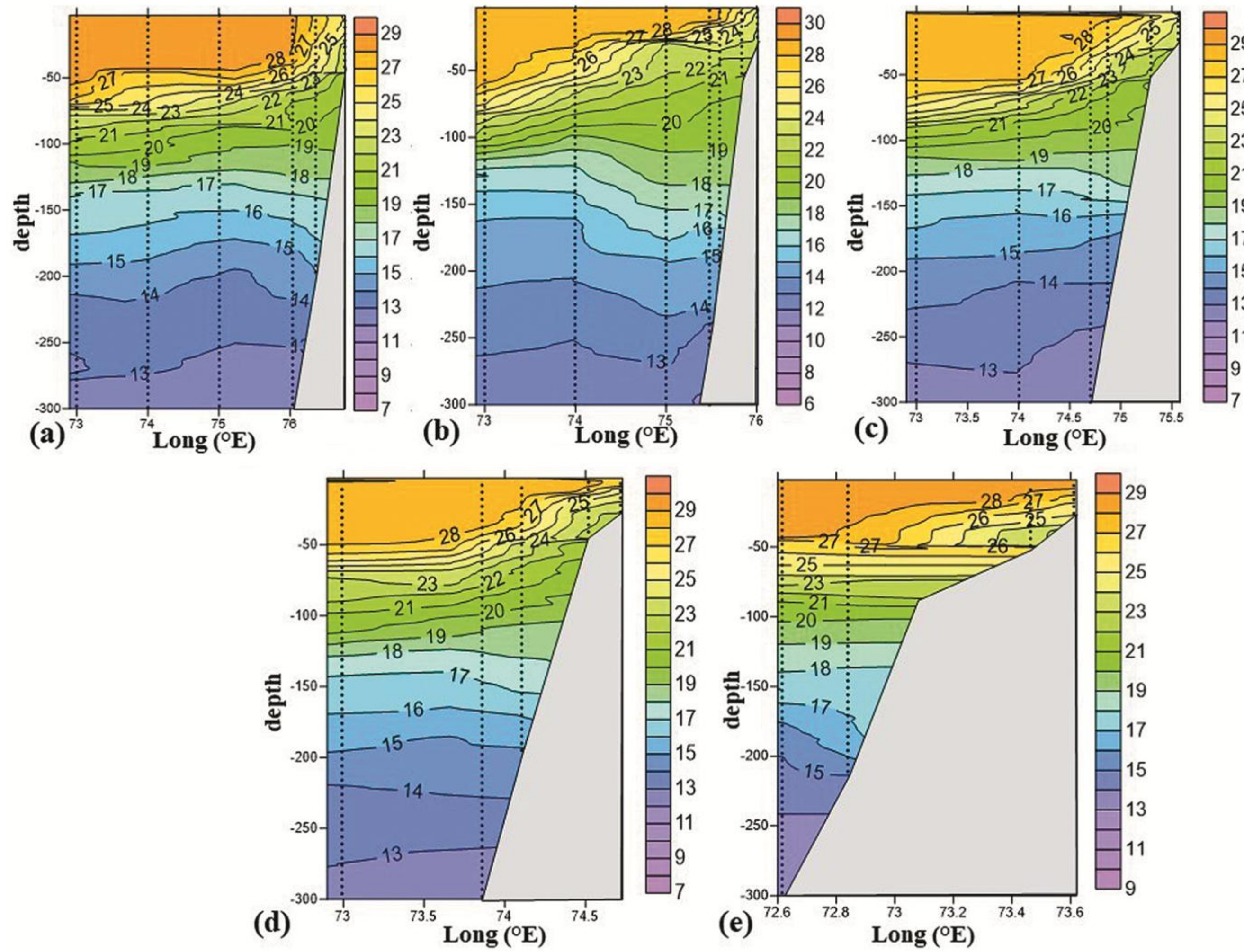

Fig. 2 — Vertical distribution of temperature along (a) Thiruvananthapuram, (b) Kochi, (c) Calicut, (d) Mangalore, and (e) Goa

coastal waters (10.8 mg m^{-3}), which decreased towards offshore (0.01 mg m^{-3}). Diatoms (91 %) composed the major phytoplankton representatives. Maximum phytoplankton abundance was observed along coastal waters (1.4×10^4 cells L^{-1}) and least towards the open ocean waters (238 cells L^{-1}). The diversity of phytoplankton showed its highest values along the shelf region (H' = 3.18) and along the offshore areas, a comparatively less diversity was observed (H' = 0.69). The phytoplankton community was represented solely by centric diatoms by more than 70 %. *Thalassiosira* sp., *Rhizosolenia alata*, *Chaetoceros curvisetus*, *Chaetoceros lorenzianus*, *Rhizosolenia* sp., etc. were the major centrales present. The other class of diatom were araphid pennates which included *Thalassionema nitzschioides*, *Thalassionema* sp., *Asterionellopsis glacialis* and *Fragilaria oceanica*. Raphid pennates included *Haslea* sp., *Pleurosigma* sp. and *Pseudo-nitzschia* sp. While dinoflagellates were dominated by thecate forms by 77 %, including *Tripos* sp., *Tripos fusus*, *Tripos furca*, *Protoperidinium* sp., etc. Other sub-classes were Dinophysiphycidae, Prorocentrophycidae and Noctilucophycidae.

Kochi transect

In Kochi, the average surface chlorophyll-*a* concentration was 2.1±2.34 mg m^{-3}. High chlorophyll-*a* concentration was found in coastal waters (6.02 mg m^{-3}) that decreased towards offshore (1.03 mg m^{-3}). This transect was mainly represented by diatoms (97 %). Maximum phytoplankton abundance was observed along coastal waters (3.2×10^4 cells L^{-1}) and least towards the open ocean waters (1.2×10^3 cells L^{-1}). Maximum phytoplankton diversity was found in the shelf region (H' = 3.57), which decreased towards offshore areas (H' = 0.78). Centric diatoms dominated by 91 % and mainly included *Thalassiosira* sp., *Rhizosolenia alata*, *Chaetoceros curvisetus*, *Chaetoceros* *lorenzianus*, *Rhizosolenia* sp., *Odontella* sp., *Lauderia* sp., etc. Raphid pennates included *Cylindrotheca closterium*, *Navicula* sp., *Nitzschia* sp., *Nitzschia longissima* and *Pleurosigma* sp. Araphid pennates were few in number. Dinoflagellates population was dominated by athecate dinoflagellate. They consisted of about 58 %, composed mainly of *Dinophysis* sp., *Dinophysis caudata* and *Ornithocercus* sp.

Calicut transect

The average surface chlorophyll-*a* concentration along the Calicut was 1.45±1.35 mg m^{-3}. High chlorophyll-*a* concentration was found in coastal waters (3.37 mg m^{-3}) that decreased towards shelf (0.23 mg m^{-3}), which further increased towards offshore (0.47 mg m^{-3}). Diatoms dominated the phytoplankton community by 98 %. Maximum phytoplankton abundance was observed along coastal waters (3.3×10^3 cells L^{-1}) and least towards offshore waters (136 cells L^{-1}). The diversity of phytoplankton was found to be maximum in the coastal region (H' = 3.39), and offshore areas had lesser diversity (H' = 1.7). Centric diatoms dominated by 90 % and included *Thalassiosira* sp., *Rhizosolenia hebetata*, *Odontella* sp., *Rhizosolenia* sp., *Chaetoceros* sp., *Guinardia striata*, etc. Araphid pennates included *Thalassionema nitzschioides*, *Asterionellopsis glacialis* and *Thalassionema* sp. Raphid pennates were rarely present. Athecate dinoflagellate dominated by 68 % and included *Protoperidinium* sp., *Ornithocercus* sp., *Tripos* sp., *Tripos fusus*, *Tripos furca*, etc.

Mangalore transect

The average surface chlorophyll-*a* concentration along Mangalore was 1.87±1.36 mg m^{-3}. High chlorophyll-*a* concentration was found in coastal waters (3.98 mg m^{-3}) and least towards open waters (1.2 mg m^{-3}). Diatoms dominated the phytoplankton community by 91 % and maximum abundance was observed along coastal waters (3.6×10^3 cells L^{-1}), while the shelf waters had the least number (140 cells L^{-1}). The diversity of phytoplankton was found to be maximum in the shelf region (H' = 3.36) and decreased towards the offshore area (H' = 1.03). Centric diatoms dominated by 98 % and included *Lauderia* sp., *Ditylum brightwellii*, *Bacteriastrum* sp., *Chaetoceros* sp., *Thalassiosira* sp., etc. Araphid and raphid pennates were present in the least number. Dinoflagellates population was generally dominated by thecate dinoflagellate by 57 % and included *Protoperidinium* sp., *Prorocentrum* sp., *Tripos* sp., spore, *Ornithocercus magnificus*, etc.

Goa transect

The average surface chlorophyll-*a* concentration along Goa was 2.2±2.75 mg m^{-3}. High chlorophyll-*a* concentration was found in the coastal waters (6.3 mg m^{-3}) that decreased towards the offshore waters (0.33 mg m^{-3}). This transect was mainly represented by diatoms (91 %). Maximum phytoplankton abundance was observed along coastal waters (1×10^4 cells L^{-1}) and least towards shelf waters (140 cells L^{-1}). The diversity of phytoplankton was found to be maximum in the 50 m depth coastal region (H' = 4.52), and 30 m depth coastal waters had comparatively lesser diversity (H' = 2.5). Centric diatoms dominated by 91 % and included *Skeletonema costatum*, *Thalassiosira* sp., *Ditylum brightwellii*, *Chaetoceros* sp., *Odontella* sp., etc. Araphid pennates included *Thalassionema nitzschioides* and *Thalassionema* sp. and raphid pennates were present in the least number. Thecate dinoflagellates dominated by 75 % and included *Protoperidinium* sp., *Prorocentrum* sp., spore, *Tripos* sp., *Dinophysis caudata*, *Dinophysis miles*, etc.

Discussion

The commencement of the upwelling process along the southwest coast of India is usually marked by the onset of the summer monsoon (May – June). During this period, a weak to moderate upwelling is obseved along the Kanyakumari coast and with the advancement of monsoonal season it spreads towards the north through the west-coast, thereby ending at the Goa coast by the peak of monsoon (July – August)[15]. Usually during this period, the winds blowing over the Arabian Sea are southwest, but along the west coast of India they become northerly. The upwelling process is identified by the variations in temperature, wind and salinity distribution.

Based on the analysis of various physico-chemical parameters along the study area, upwelling was well evident along the southern region (off Thiruvananthapuram) along the nearshore waters with propagation to the offshore areas. The SST pattern, as well as 24 °C isotherm along the transect, observed a dip in temperature up to the shelf waters which extended to the open ocean regions in the subsurface layers. The surface distribution of temperature observed comparatively cooler waters towards the south that increased in temperature northward. The study period is during the onset to the peak phase of the summer monsoon and during the period the signatures of upwelling are well established as in previous studies[21-27]. The region off Thiruvananthapuram is previously reported to have moderate to intense upwelling throughout the monsoon period[28]. This might be due to the wind pattern and other remote forcing acting in the area[17]. Upsloping of 24 ℃ isotherm from 75 m to the surface in coastal areas were observed along the transect. The vertical profiles of temperature indicated intense upwelling along the coastal water of Thiruvananthapuram transect extending towards the shelf and open ocean waters.

Signatures of upwelling were very well evident along the coastal waters off Kochi extending towards the shelf region. However, the process decreased towards the open ocean waters suggesting a weak offshore transport[17]. Vertical profile of temperature indicates upsloping of 24 ℃ isotherm from 75 m in the open ocean waters to sub-surface (20 m) in the coastal waters indicating upwelling occurring in the nearshore and shelf waters. Summer monsoon upwelling, variations in the current pattern and influx of freshwater from adjacent Cochin estuary defines the characteristics of the coastal waters off Kochi[29]. However, towards off Calicut, the intensity of upwelling was much lesser and confined clearly towards the nearshore waters. The vertical profile along the transect showed clear indications of coastal upwelling with upsloping of 24 ℃ isotherm to the near-surface whereas; towards the north, upwelling signatures were much lesser and was not evident along the off Goa with almost stratified waters.

During the study period, the surface distributions, as well as the vertical profiles of salinity, observed the occurrence of low saline surface waters in the nearshore areas off Mangalore and Goa (Fig. 3). This might be due to the influx of fresh water in the region and was previously established in various studies[30-31].

Principal component analysis of various physico-chemical factors in different stations of the study area revealed that PC1 and PC2 clearly demarcated the transects with a cumulative variations of 54.3 %. An addition of PC3 contributed a cumulative variation of 74 %. Analysis of PCA indicated high chlorophyll-*a*, low SST, and comparatively higher nutrient concentrations towards the coastal waters characterized by coastal upwelling. Moreover, a strong negative correlation was observed between chlorophyll-*a* concentration and SST in the study area (Fig. 4) as the production decreases with increase in temperature as stated by Bhattathiri *et al.*[1].

During south-west monsoon, the progressive replacement of surface waters by deeper nutrient-rich waters as a result of upwelling is said to enhance the productivity in the southern parts of the Arabian Sea. The high concentration of nitrate, phosphate and silicate (3±0.54 µmol L^{-1}, 1.2±0.9 µmol L^{-1} and

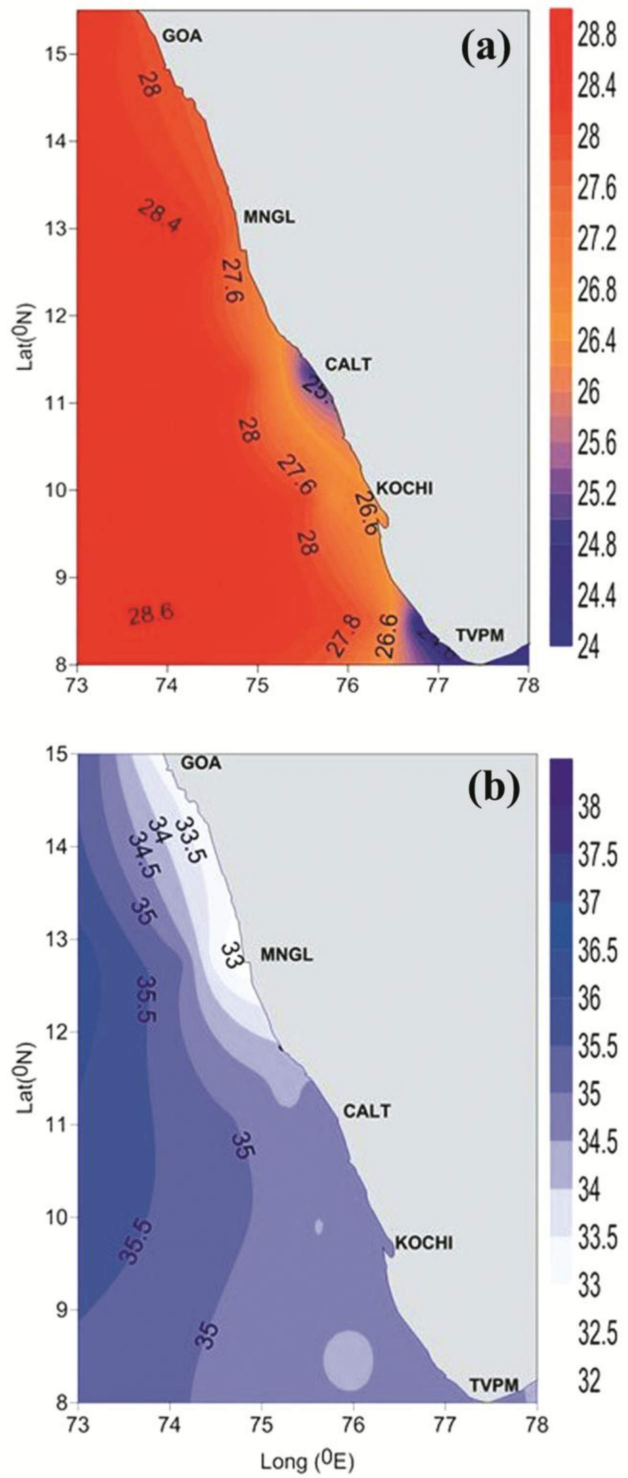

Fig. 3 — Surface distribution of (a) Temperature, and (b) Salinity along different transects

15±5.8 μmol L^{-1}, respectively) along the southern transects indicated a vertical flux of nutrients from the deeper depths. A high chlorophyll-*a* concentration was observed along the coastal waters of the southern transects, with a peak towards the coastal waters off Thiruvananthapuram (10.8 mg m^{-3}), followed by off Kochi coastal waters (6.02 mg m^{-3}). Although along off Mangalore and off Goa, where upwelling was confined to narrow coastal zone, a high chlorophyll-*a* (3.98 and 6.31 mg m^{-3}) was observed. This may be due to the intense land runoff and estuarine water influx from the Nethravati-Gurupur and Zuari- Mandovi estuaries along the west coast near Mangalore and Goa[32].

During the study highest average phytoplankton cell density was observed along off Thiruvananthapuram (1.2×10^4 cells L^{-1}), with maximum cell density along coastal waters (3.2×10^4 cells L^{-1}) that persisted towards the shelf and open waters. Phytoplankton cell density off Kochi was observed to be highest along the coastal upwelling region with an average of 1.3×10^4 cells L^{-1}, and subsequently, high values of biomass are obtained towards the offshore region due to sub-surface upwelling along the shelf and offshore region. Off Calicut had high phytoplankton cell density along the coastal upwelling region with an average of 1.9×10^4 cells L^{-1}. However, the cell density was observed to be significantly low in the shelf and offshore regions. In off Mangalore and Goa, high phytoplankton cell density was observed even though there was only slight upwelling.

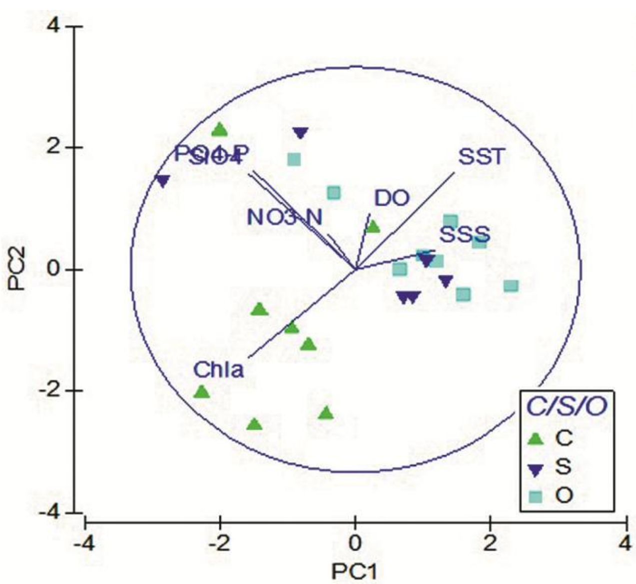

Fig. 4 — PCA analysis showing ordination of various stations in accordance with the variations in different physico-chemical parameters

Phytoplankton community off Thiruvananthapuram was merely represented by diatoms, with a few representatives of dinoflagellates. Centric diatoms dominated the community with 70 % of the total cell density. *Thalassiosira* sp. was abundant among the centric diatoms (37 %) and the other main diatoms were *Asterionellopsis glacialis* and *Chaetoceros curvisetus*. These species were previously reported from upwelling regions and were regarded as the functional groups of these euthropic waters[33].

The K-dominance plot made for the average phytoplankton composition of the coastal shelf and open waters observed higher diversity along the coastal and shelf waters than in the open ocean region (Fig. 5). The studies on the upwelling associated phytoplankton community had previously recorded an increased diversity along the coastal waters that decreased towards offshore[28]. The Non-metric Multidimensional Scaling analysis (NMDS) using the community structure of phytoplankton observed two major groups, Group A and Group B. The analysis shows a clear demarcation between the community composition of upwelled, mild upwelled and non-upwelled waters. Group A included mainly non-upwelled waters with some representation from mild upwelled, whereas Group B included mainly upwelled and mild upwelled waters. It was observed that there was 60 % similarity in phytoplankton composition between stations with upwelled waters, as most of the upwelled waters were dominated by centric diatoms (Subclass: Coscinodiscophycidae; Fig. 6).

Hence, the present study provides an account on the phytoplankton community structure along with the

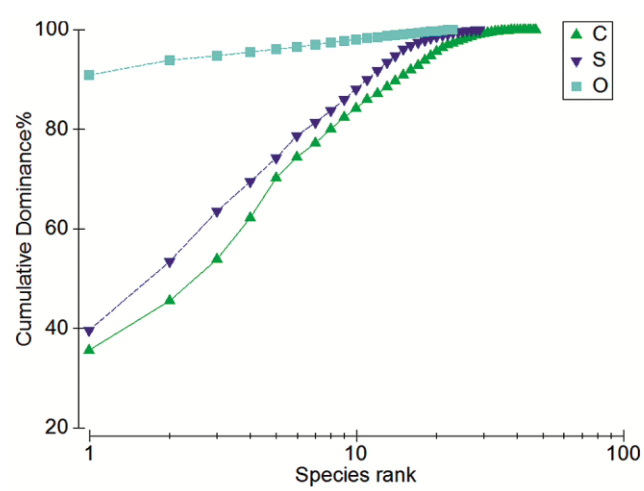

Fig. 5 — Showing phase wise *k*-dominance plot for the phytoplankton composition during the study period along SEAS

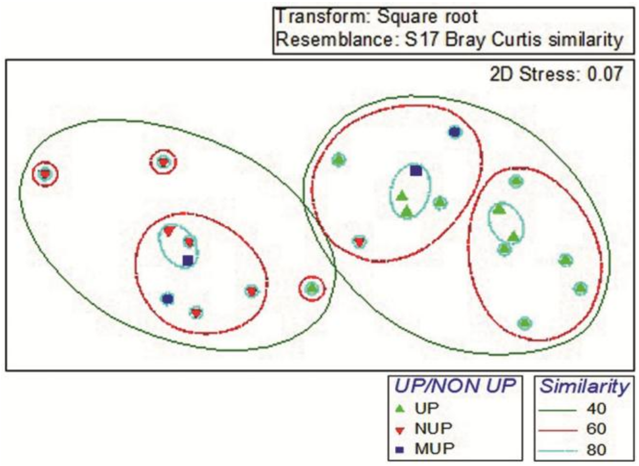

Fig. 6 — Non-metric Multidimensional Scaling analysis (NMDS) plot for the study area using the phytoplankton community structure

physico-chemical characteristics of SEAS during upwelling. As the survey covered both the upwelled and non–upwelled waters, a comparison was made between the two. The study also highlights coast–offshore variations in phytoplankton assemblage along the SEAS. To conclude, this work provides baseline information on the hydrobiological characteristics and community structure of microphytoplankton along the South Eastern Arabian Sea (SEAS) during early Summer Monsoon (SM) which would be useful for further studies on trophodynamics of SEAS during productive summer monsoon season.

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Conflict of Interest

The authors declare that they have no conflict of interest.

Author Contributions

TS & LCT wrote the manuscript with input from KBP. TS conducted the field study. TS & LCT conducted taxonomic identifications. KBP supervised this study and provided research materials.

References

1 Bhattathiri P M A, Pant A, Sawant S S, Gauns M, Matondkar S G P, *et al.*, Phytoplankton production and chlorophyll distribution in the eastern and central Arabian Sea in 1994-1995, *Curr Sci*, 71 (11) (1996) 857-862.

2 Goldman J C & Mann R, Temperature-influenced variations in speciation and chemical composition of marine phytoplankton in outdoor mass cultures, *J Exp Mar Biol Ecol*, 46 (1) (1980) 29-39.

3 Ryther J H, Photosynthesis in the ocean as a function of light intensity, *Limnol Oceanogr*, 1 (1) (1956) 61-70.

4 Estrada M & Berdalet E, Phytoplankton in a turbulent world, In: *Lectures on plankton and turbulence*, edited by C Marrase, E Saiz & J M Redondo, (Scientia Marina), 1997, pp. 125-140.

5 Sanders J G, Cibik S J, D'Elia C F & Boynton W R, Nutrient enrichment studies in a coastal plain estuary: changes in phytoplankton species composition, *Can J Fish Aquat Sci*, 44 (1) (1987) 83-90.

6 Brink K, Abrante F, Bernal P, Estrada M, Hutchings L, *et al.*, Group report: how do coastal upwelling systems operate as integrated physical, chemical, and biological systems and influence the geological record? The role of physical processes in defining the spatial structures of biological and chemical variables, In: *Upwelling in the Oceans: Modem Processes and Ancient Records*, edited by C Summerhayes, K Emeis, M Angel, R Smith & B Zeitzschel, (John Wiley and Sons), 1995, pp. 103-125.

7 Wollast R, Evaluation and comparison of the global carbon cycle in the coastal zone and in the open ocean, In: *The Sea*, edited by K Brink & A Robinson, (Johns Wiley & Sons), 1998, pp. 213-251.

8 Estrada M & Blasco D, Phytoplankton assemblages in coastal upwelling areas, In: *Simposio International sobre las Areas de afloramiento mas importantes del Oeste Africano*, edited by C Bas, R Margalef & P Rubies, (Ins InvPesq CSIC, Barcelona), 1985, pp. 379-402.

9 Tilstone G H, Miguez B M, Figueiras F G & Fermín E G, Diatom dynamics in a coastal ecosystem affected by upwelling: coupling between species succession, circulation and biogeochemical processes, *Mar Ecol Prog Ser*, 205 (2000) 23-41.

10 Subrahmanyan R, Phytoplankton organisms of the Arabian Sea off the west coast of India, *J Indian Bot Soc*, 37 (4) (1958) 435-441.

11 Qasim S Z & Reddy C V G, The estimation of plant pigment of Cochin backwater during monsoon months, *Bull Mar Sci*, 17 (1967) 95-110.

12 Radhakrishna Y & Ganapati P N, Fauna of the Kakinada bay, *Bull Natl Inst Sci India*, 38 (1969) 49-79.

13 Subrahmanyan R, Gopinathan C P & Pillai C T, Phytoplankton of the Indian ocean: some ecological problems, *J Mar Biol Assoc India*, 17 (3) (1975) 608-612.

14 Habeebrehman H, Prabhakaran M P, Jacob J, Sabu P, Jayalakshmi K J, *et al.*, Variability in biological responses influenced by upwelling events in the Eastern Arabian Sea, *J Mar Syst*, 74 (2008) 545-560.

15 Sharma G S, Thermocline as an indicator of upwelling, *J Mar Biol Assoc India*, 8 (1966) 8-19.

16 Unnikrishnan A S & Antony M K, On an upwelling front along the west coast of India during later part of southwest

monsoon, paper presented at the *Symposium on Physical processes in the Indian Seas, ISPSO*, 1992.

17 Smitha B R, Sanjeevan V N, Vimalkumar K G & Revichandran C, On the upwelling off the southern tip and along the west coast of India, *J Coast Res*, 24 (2008) 95-102.

18 Parsons T R, Maita Y & Lalli C M, *A manual of chemical and biological methods for seawater analysis*, (Pergamon Press, New York), 1984, pp. 173.

19 Grasshoff K, Ehrhardt M, Kremling K & Almgren T, *Methods of seawater analysis*, (Verlag Chemie, Weinheim), 1983, pp. 419.

20 Tomas C R, *Identifying Marine diatoms and dinoflagellates*, (Academic press, New York), 1997.

21 Banse K, On upwelling and bottom-trawling off the southwest coast of India, *J Mar Biol Assoc India*, 1 (1959) 33-49.

22 Banse K, Hydrography of the Arabian Sea shelf of India and Pakistan and effects on demersal fishes, *Deep-Sea Res*, 15 (1968) 45-79.

23 Sharma G S, Seasonal variation of some hydrographic properties of the shelf waters off the west coast of India, *Bull Nat Inst Sci*, *India*, 38 (1968) 263-276.

24 Shetye S R, Seasonal variability of the temperature field off the south-west coast of India, *Proc Indian Acad Sci (Earth Planet Sci)*, 93 (4) (1984) 399-411.

25 McCreary J P & Chao S Y, Three-dimensional shelf circulation along an eastern ocean boundary, *J Mar Res*, 43 (1985) 13-36.

26 Johannessen J A, Johnnessen O M, Svendsen E, Shuchman R, Manley T, *et al*., Mesoscale eddies in the Fram Strait marginal ice zone during the 1983 and 1984 Marginal Ice Zone Experiments, *J Geophys Res Oceans*, 92 (1987) 6754-6772.

27 Shetye S R, Gouveia A D, Shenoi S S C, Sundar D, Michael G S, *et al*., Hydrography and circulation off the west coast of India during the southwest monsoon 1987, *J Mar Res*, 48 (1990) 359-378.

28 Lathika C T, Padmakumar K B, Smitha B R, AshaDevi C R, Bijoy N S, *et al*., Spatio-temporal variation of microphytoplankton in the upwelling system of the southeastern Arabian Sea during the summer monsoon of 2009, *Oceanologia*, 55 (2013) 185-204.

29 Madhupratap M, Status and strategy of zooplankton of tropical Indian estuaries: a review, *Bull Plankton Soc*, *Japan*, 34 (1987) 65-81.

30 Shetye S R, Dileepkumar M & Shankar D, *The Mandovi and Zuari Estuaries* (National Institute of Oceanography, Goa, India), 2007, pp. 145.

31 Shruthi M S & Rajashekhar M, Ecological observations on the phytoplankton of Netravathi-Gurupura estuary, Southwest coast of India, *J Mar Biol Assoc India*, 55 (2014) 1-7.

32 Gurumurthy G P, Tripti M, Riotte J, Prakyath R & Balakrishna K, Impact of water-particle interactions on molybdenum budget in humid tropical rivers and estuaries: insights from Nethravati, Gurupur and Mandovi river systems, *Chem Geol*, 450 (2017) 44-58.

33 Lassiter A M, Wilkerson F P, Dugdale R C & Hogue V E, Phytoplankton assemblages in the CoOP-WEST coastal upwelling area, *Deep Sea Res*, 53 (2006) 3063- 3077.