

Biophysical implications of the freshwater influx over small spatial scale in the coastal waters along the southwest coast of India during the Southwest Monsoon

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Abstract

This study in the coastal waters off Kochi along the southwest coast of India during the Southwest Monsoon (SWM) presents the biophysical implications of freshwater influx over a small spatial scale. Field sampling was carried out along two cross-shore transects (ST and NT), oriented ~ 8 km apart, and located to the south (ST) and north (NT) of the Kochi inlet, up to the depth of 50 m. The vertical profiles of temperature and dissolved oxygen showed clear upwelling signatures along both ST and NT, but more prominently along the latter transect. The freshwater influx and its southward advection due to the prevailing coastal currents caused stronger salinity stratification along ST and inhibited the rising of upwelled waters in the nearshore waters. The integrated phytoplankton biomass (chlorophyll *a*) in the upper 10 m was markedly higher along NT (50 mg m⁻³) compared to ST (35 mg m⁻³). The size-based phytoplankton biomass showed an increase in larger size (micro) fraction of phytoplankton along NT especially in the nearshore waters, wherein upwelling was prominent up to the surface waters. The more efficient surfacing of oxygen-deficient waters along NT cause more likely chances to concentrate small pelagic fishes there as compared to ST. Thus, this study presents a case, wherein, the freshwater influx and associated inhibition of coastal upwelling in the nearshore waters vary within a short spatial scale depending upon the advection of freshwater plume by the coastal currents. Also, showed that this situation might be valid to many estuarine inlet regions along the southwest coast of India during the SWM.

Keywords: upwelling, hypoxia, phytoplankton, monsoon, southeastern Arabian Sea.

1. Introduction

The Southeastern Arabian Sea (SEAS) has warm waters, weak winds, low rainfall, and low phytoplankton production during the Pre-SWM (March-May) and this situation changes drastically by the SWM (SWM; June -September) characterized by strong winds, cooler waters, heavy rainfall and a significant increase in phytoplankton production (Jyothibabu et al., 2010; Anjusha et al., 2018; Karnan et al., 2020). The coastal upwelling is the main causative factor that significantly lowers the water column temperature and enhances phytoplankton production in the SEAS during the SWM. Studies have shown that initial signals of upwelling along the southwest coast of India appear around February - March in the deeper layers, which gets discernible in the shelf waters by late May (Gupta et al., 2016; Sharma, 1978; Banse, 1959). The SEAS also receives freshwater influx from more than 50 rivers that originate in the Western Ghats (Jyothibabu et al., 2010; Anjusha et al., 2018). Though these rivers are short (av. length 64km), they have a cumulative effect on the hydrography in the nearshore waters along the Indian western coastline (Jyothibabu et al., 2010). They flow swiftly due to the steeper topography of Western Ghats and the adjoining land and cumulatively drain a huge amount of fresh water to the estuaries and then to the coastal waters of the SEAS (Jyothibabu et al., 2010). The resulting hydrographical setting of the nearshore waters of the SEAS significantly alters the biological productivity of the region especially during the SWM (Anjusha et al., 2018; Madhu et al., 2010; Jyothibabu et al., 2008). In the present study, we selected the nearshore waters off Kochi, along the southwest coast of India, wherein Kochi backwaters (KBW) discharges huge freshwater influx (22000 metric cubes annually) gathered from seven rivers (Revichandran et al., 2012). KBW is a tropical, micro-tidal estuarine system (tidal range <1m) situated along the southwest coast of India. It is considered as a typical monsoonal estuary that manages heavy precipitation and freshwater influx it accumulates during the SWM (Vijith et al., 2009).

Past studies observed that the coastal waters off Kochi at 10°N along the southwest coast of India experiences moderate to intense upwelling during the SWM (Ramamirtham and Jayaraman, 1960; Smitha et al., 2008; Gupta et al., 2016; Anjusha et al., 2018; Karnan et al., 2020). So in effect during the SWM, the coastal water of Kochi is exposed to a large freshwater influx from the landside and upwelling of cold nutrient-rich subsurface waters from the seaside. The freshwater influx during SWM induces stratification in the water column (Karnan et al., 2020; Anjusha et al., 2018; Jyothibabu et al., 2010; Ramamirtham and Jayaraman, 1960). It was noticed from many parts of the world that heavy freshwater influx in the coastal waters inhibits the upwelling of the subsurface waters (Table 1). The low saline surface waters inhibit the surfacing of subsurface macronutrients and their availability to the phytoplankton in the surface layers (Iriarte et al., 2007). But, as valid in the present case,

estuarine influx also brings nutrient-rich waters to the nearshore waters, and therefore, there may not be a shortage of the overall concentration of macronutrients in the surface waters (Anjusha et al., 2018). However, it is still unclear about various biophysical implications of the freshwater influx in the nearshore waters and more so on its variation over a short spatial scale along the coastline in the study domain. This is particularly important as the plume movement and dispersal heavily depend upon the coastal currents prevailing in a region (Wiseman and Garvine, 1995). Therefore, this study investigates some of the biophysical implications of the freshwater influx in the study domain over a short spatial scale. The objectives of this study are (a) to track the impact of the freshwater influx in the nearshore waters off Kochi and its variations over the small spatial distance during SWM. (b) to understand the impact of the freshwater influx on the phytoplankton community structure in the nearshore waters off Kochi during the SWM and (c) to infer the possible local impact of freshwater influx on the surfacing tendency of small schooling pelagic fishes as a response to hypoxic upwelled waters during the SWM.

2. Materials and methods

KBW is the largest estuarine system along the southwest coast of India located between 9° 40' and 10° 12'N and 76° 10' and 76° 30' E (Figure 1). The average annual rainfall here is 3.2m about in which 75% occurs during the SWM (Qasim, 2003). A huge amount of freshwater ($\sim 22 \times 10^3$ Mm³/year) from the seven rivers (Pamba, Achancoil, Manimala, Meenachil, Muvattupuzha Periyar and Chalakkudy) reaches the KBW. During the peak SWM, the entire stretch of the KBW is freshwater dominant and the hydrography resembles that of a freshwater lake (Madhupratap, 1987; Jyothibabu et al., 2006). KBW flushes into the neighbouring SEAS through two inlets, Kochi and Azheekode/Munambam, in which the former is much wider and thus function as the main entrance to the SEAS (Joseph and Kurup, 1989).

Kochi coastal waters, a part of the Indian southwestern inner shelf, has noticeable seasonal changes in hydrography by the onset of the SWM (Figure 2). It is also heavily influenced by the KBW influx especially during the SWM and the intensity of which is governed mainly by the phase of the tide and the coastal currents (Anjusha et al., 2018; Karnan et al., 2020; Seena et al., 2020). In this study, two cross-shore transects off Kochi up to a depth of 50m were sampled during the SWM (September) of 2018 onboard *CRV Sagar Purvi*. The two transects were oriented ~ 8 km apart, wherein, the Northern Transect (NT) and the Southern Transect (ST) were located in the north and south of the Kochi inlet, respectively. Along these cross-shore transects, three stations were sampled at varying depth of 10 m, 30 m, and 50 m (Figure 1). The nearshore station of ST and NT was 4 km away from the coast, whereas, the 30 and 50 m depth stations were 15 and 17 km away from the

coastline, respectively. The vertical profiles of temperature, salinity, and turbidity were recorded using Conductivity Temperature Depth (CTD) profiler (Seabird Electronics). According to CSIR-NIO Atlas (Chatterji et al., 2012), salinity prevailing beyond the shelf of the SEAS during SWM is 34.8. This offshore salinity (34.8) is considered in this study for demarcating the freshwater influenced water column in the surface layer. Water samples were collected from discrete depths (surface, mid, and bottom) to measure the chemical and biological parameters using Niskin samplers. Water samples for chemical (dissolved oxygen and nutrients) and phytoplankton biomass (chlorophyll *a*) were taken from the surface, middle, and near the bottom. In 10 m station the surface, mid and bottom samples were collected from 0 m, 5 m and 9 m and in 30 m station the surface water was from 0 m 15 m and 29 m respectively. In 50 m station, the surface sample was from 0 m, mid from 25 m and the bottom sample was from 49m. Throughout the sampling period, the sea stayed moderately calm. The estimation of dissolved oxygen was done by Winkler's titration method. Macronutrient was measured spectrophotometrically following the standard method (Grasshoff et al., 1983). The total phytoplankton biomass (chlorophyll *a*) was measured by filtering 0.5 L of water sample through cellulose nitrate filters (0.22 μm) and subsequent extraction using 10 ml 90% acetone. The extracted chlorophyll-*a* was estimated using a calibrated Trilogy Turner Fluorometer following the standard procedure (UNESCO, 1994). The size-based fractionation of phytoplankton on filters was carried out following the standard stepwise serial filtration procedure (Madhu et al., 2010; Jyothibabu et al., 2018) and the estimation of chlorophyll-*a* was carried out by the same procedure given above. The study region is exposed to semidiurnal tide with a maximum tidal height of <1m (Qasim and Gopinathan, 1969). The two transects in the present study were sampled at the same time on adjacent days (12th and 13th September 2018) and therefore the locations sampled in both transects experienced the same tidal phase.

The interrelationships within and between the environmental variables (temperature, salinity, turbidity, nutrients and dissolved oxygen) and the biological variables (picoplankton, nanoplankton, microplankton and chlorophyll-*a*) were analysed using RDA (CANOCO 4.5). RDA (Redundancy analysis) is a direct gradient analysis technique, which summarises linear relationships between components of response variables that are explained by a set of explanatory variables. Initially, the data was tested with Detrended Correspondence Analysis for finding a suitable ordination technique. The Detrended Correspondence Analysis results showed axis gradient length < 2, suggesting the use of a linear multivariate RDA as the most suitable method (Leps and Smilauer, 2003). The biological variables were log-transformed before the analysis. In Monte Carlo test, the variations described by the clarifying variables in the constrained ordination is tested and the significant variables are

measured for interpretation. In complete RDA, the major hydrographical parameters measured (salinity, temperature, nitrate, silicate, phosphate and turbidity) are considered for explaining the overall variance of the biological components. In partial RDA analyses, salinity was considered as the principal variable, and others as co-variables for interpreting the biological variables. For visualization of the results, RDA was represented in Triplot in which points display sampling locations, and biological (blue lines) and environmental variables (red lines) were displayed by arrows. The spatial and seasonal changes in the environmental parameters and the biological variables were tested with ANOVA. First, datasets were tested for their distribution and homogeneity. For data sets with normal distribution, parametric ANOVA was performed, whereas, a non-parametric ANOVA (Kruskal-Wallis) was used for the abnormal data distribution. The normality test, parametric ANOVA and Non- parametric ANOVA were performed in XL-Stat Pro software package.

3. Result and discussion

3.1. Hydrographical difference between ST and NT

The study area is characterized by the stronger winds (6 m/s), cooler SST (26 °C), and significantly higher rainfall (0.4 mm/hr) during the SWM as compared to the Pre-Monsoon period (Figure 2). Although the two transects sampled (ST and NT) were located 8km apart in the north and south of Kochi inlet in the coastal waters, their hydrographical characteristics showed some salient features. The vertical distributions of temperature and salinity along these transects are presented in Figure 3. The shoaling up of isotherms towards the coast was evident in both transects, which indicated the occurrence of coastal upwelling (Figure 3a). The vertical profile of temperature showed cooler surface waters along the ST compared to the NT (Figure 3b). The vertical distribution of salinity showed noticeable freshwater plume in the nearshore waters in ST, whereas, such a clear feature was absent in NT. An estimate of the surface water column influenced by the freshwater influx (32.8 as demarcating salinity) showed that around 20m of the water column at 50m depth in ST was influenced by the freshwater influx. But it was <10m water column influenced by the freshwater at 50m locations in NT. The salinity stratification (Brunt–Väisälä frequency) was found to be stronger in the inshore regions of ST compared to NT (Figure 3c). The turbidity level in the surface waters was noticeably higher along ST compared to NT (Figure 3d), and the concentration of dissolved oxygen in the surface waters along both transects was noticeably higher than the subsurface waters (Figure 3e). However, along both transects the upsloping of low oxygenated waters towards the coastline, a typical coastal upwelling feature along the southwest coast of India, was evident. The surfacing of the low oxygenated waters from the deep was found to be more

prominent along NT as compared to ST. The shallowing of isolines of temperature, salinity, and dissolved oxygen in the ST and NT on a relative basis is presented in Figure 4. This clearly shows that the isolines of all parameters considered were found to be at much shallower depth along NT indicating a stronger upwelling along that transect compared to ST. The enrichment of macronutrients in the surface waters was well marked in both the transects (Figure 5). The nitrate concentration in the water column was found to be higher along NT than in ST. But in the nearshore surface waters, ST showed an increased concentration of nitrate than NT. The distribution of phosphate was similar to that of nitrate distribution. The nearshore region of ST was found high in phosphate. The silicate concentration was generally high in all stations sampled with an exceptionally high concentration in the nearshore locations of ST.

The insightful studies in the 1950s showed the occurrence of upwelling along the west coast of India and its biophysical implications (Ramasastry and Myrland, 1959; Banse, 1959, 1968). Upwelling along the SEAS begins in the outer shelf waters (100 m) by January though its signatures in the nearshore waters are perceivable only by early June (Shenoi et al., 2005; Jyothibabu et al., 2010). Since biological signatures of coastal upwelling are noticed from June onwards till September, traditionally, the upwelling period is referred from June to September in biological studies (Banse, 1959; Habeebrehman et al., 2008; Jyothibabu et al., 2010). Usually, the upwelling along the SEAS is attributed to the offshore Ekman transport primarily driven by the steady and a strong westerly/northwesterly wind ($> 7\text{m/s}$), which brings up the subsurface waters (100-150m) along the coastline (Smitha et al., 2008; Gupta et al., 2016; Hareesh Kumar and Anand, 2016). But it was noted in many other studies that the initiation of upwelling begins in the deeper outer shelf waters as early as January, much before the strong and steady monsoon winds sets in the region. This observation led to the finding of the role of remote forcing (Kelvin waves) inducing coastal upwelling along the SEAS (McCreary et al., 1996; Shankar and Shetye., 1997; Hareesh Kumar and Anand, 2016). On the other hand, it has been well-established since the 1960s that upwelling plays a crucial part in increasing plankton production in the Indian south-western shelf during the SWM. But the understanding of how close the upwelled waters reach in different parts of the Indian western coastline is still limited. A historical study showed that upwelled waters intrude into the estuarine bottom along the southwest coast of India through deep channels in the inlets (Sankaranarayanan and Qasim, 1969). Our recent studies along the coastal region of Alappuzha (southcentral Kerala) evidenced that upwelled waters reach very shallow waters, even less than 5m depth, in regions which are far away from the river/estuarine inlets and devoid of low saline capping on the surface (Jagadeesan et al., 2017; Karnan et al., 2017).

As evident in Table 1, the heavy freshwater influx from rivers can suppress the upwelling in the nearshore waters. Therefore, the high plankton production occurring in the near-shore waters along the southwest coast of India during the SWM is contributed by both the coastal upwelling and river influx on varying scales (Banse, 1959; Madhupratap et al., 1990; Nair et al., 1992). Quite logical to consider that the estuarine influx could alter the distribution of salinity and surface layer stratification in the coastal area (Banse, 1959, Jyothibabu et al., 2008; Miller C B, 2009; Anjusha et al., 2018). As the freshwater plume movement heavily depends on the coastal current prevailing in an area (Wiseman, and Garvine, 1995), quite likely that the impact of the freshening and stratification might noticeably vary over a short spatial scale alongshore. The surface current in the study domain during the sampling period (SWM) is equatorward (Revichandran, 2004; Seena et al., 2020), and hence the low saline influx from KBW instead of spreading equally off the inlet, was directed southward. The low saline plume was found to extend up to 30m depth station along the ST which is almost 25 km from the shore. At the same time, the presence of low salinity, though in low magnitude, was evident along the NT as well. This low salinity was essentially contributed by the estuarine influx through the small northern inlet of the KBW, which empties a much lower influx to the SEAS compared to the much wider Kochi inlet (Seena et al., 2020). The increased stratification of the low saline plume in ST caused a stronger Brunt Vaisala frequency in the nearshore waters. As mentioned above, nutrient enrichment in the coastal waters along the southwest coast of India during the SWM is quite usual and is attributed to the combined effect of upwelling and river influx (Madhupratap et al., 1990; Nair et al., 1992; Jyothibabu et al., 2010). In the present case, both ST and NT showed a higher concentration of macronutrients through freshwater influx, and the resultant stratification inhibited the surfacing of the upwelled waters in the nearshore waters of the ST. Contrary to the expectation, the nearshore waters of ST showed higher concentration of nitrate and silicate compared to NT which can be attributed to the estuarine plume borne nutrients as observed earlier (Madhupratap et al., 1990; Nair et al., 1992; Jyothibabu et al., 2010).

The rainfall and the freshwater influx in the study domain peaks during the July-August period (Figure 6; Anjusha et al., 2018; Karnan et al., 2017) and hence naturally, the low salinity capping and inhibition of upwelling could be much more prominent at that period. This needs to be addressed based on more intensive and long duration data sets. Other aspects that are beyond the reach of this study are the dynamics in the freshwater influx in the study region to the tidal phases and also the lateral advection of the plumes linked to the southerly coastal currents during the SWM. Similar is the case of understanding the southward advection of upwelled waters linked with coastal currents during the SWM. These dynamic aspects of the freshwater plume and the advection of upwelled

waters need more concentrated field observations complemented with modelling studies. Considering the numerous river inlets along the southwest coast of India, it's quite likely that the low salinity plumes from these inlets, under the influence of the coastal currents, could cause spatial variations in the hydrographical setting over short distances especially on both sides of the inlets.

3.2. Biophysical implications along ST and NT

As stated before, upwelling and river influx during the SWM enhances plankton biomass and production in the nearshore waters of the SEAS (Nair et al., 1992; Madhupratap et al., 1990; Jyothibabu et al, 2008). Naturally, the first biological signature of the hydrographical changes due to any ocean processes is on the phytoplankton community as they are the primary producers and respond rapidly to various environmental fluctuations (McLusky, 1971; Cleorn, 1987; Ferreira et al., 2005). They are the most fundamental and key community that sustains the food chain in the ocean thereby the survival of almost all ocean living resources (Hilmer & Bate 1990; Adams and Bate, 1999). The result of the present study on the phytoplankton community along ST and NT showed the following striking features. The first feature was a progressive decrease in phytoplankton biomass (chlorophyll a) from the nearshore to the seaward, which is quite usual as noticed in many recent studies (Anjusha et al., 2018; Karnan et al., 2017). Secondly, there was a noticeable increase in the phytoplankton biomass in the nearshore locations in the NT compared to ST (Figure 7). Also, the integrated mean chlorophyll-a in the upper water column (10m) was noticeably higher in NT (50 mg/m^3) compared to ST (36 mg/m^3). In the surface waters, the mean total chlorophyll-*a* in the surface was measured to be 3.16 mg m^{-3} in N1 but, it was 1.93 mg m^{-3} in S1. There was a discernable increase in microplankton contribution at N1 (1.26 mg m^{-3}) compared to S1 (0.19 mg m^{-3}). At the same time, the nanoplankton contribution in both N1 and S1 were comparable in magnitude (1.60 and 1.61 mg m^{-3} , respectively). The picoplankton contribution to the total biomass was the lowest in both the N1 (0.28 mg m^{-3}) and S1 (0.13 mg m^{-3}). This trend was followed in the mid and bottom waters of both the transects as well. The presence of the more concentration of upwelled nutrients along the surface waters of NT transect could be the reason for the high phytoplankton biomass observed there. Although the macronutrients were observed to be higher in the nearshore waters of ST, this was not reflected in the chlorophyll concentration when compared to NT. This anomalous feature could be explained by understanding the composition of the phytoplankton community along these transects. The phytoplankton size-based contribution to the total chlorophyll-*a* is presented in Figure 8, which has a salient signature. In all locations and depths sampled, the contributions of microplankton were significantly higher along NT compared to ST. It is evident from many recent studies along the southwest coast of India that the upwelled nutrients significantly enhance the

biomass of the larger phytoplankton (Karman et al., 2017; Jagadeesan et al., 2017; Karnan et al., 2020). Similarly, many studies also showed that KBW influx during the SWM has more amount of smaller (nano) plankton (Madhu et al., 2010; Jagadeesan et al., 2017; Karnan et al., 2020) and therefore the estuarine plume that was spread over ST showed significantly more amount of nanoplankton as compared to NT. In essence, this study evidenced that a stronger freshwater plume and inhibition of upwelling along the ST influenced a measurable change in the size of the phytoplankton community over a short spatial scale.

Numerous studies have shown that concentration of fish stock in the surface waters along the Southwest coast of India during the SWM heavily depends on the dissolved oxygen levels (Banse, 1959; Reghunathan et al., 1984; Nordlie, 2006). The upwelled low oxygenated waters concentrate the fishes to the surface waters along the Southwest coast of India during the SWM (Banse, 1959; Reghunathan et al., 1984; Karnan et al., 2017). During the coastal upwelling period, the rising of cooler oxygen-deficient waters in the outer Indian western shelf tend to push demersal fishes towards the nearshore waters and then to the surface layers (Banse, 1959, Reghunathan et al., 1984; Karnan et al., 2017). Similarly, small schooling pelagic fishes in the nearshore waters undergo an upward shift to avoid the low oxygenated condition of upwelled waters, eventually making their increased availability in the surface layers (Reghunathan et al., 1984; Karnan et al., 2017). It is interesting to consider these features over small spatial scale considering the hydrographical settings along ST and NT. The NT was much more influenced by the coastal upwelling and associated surfacing of low oxygenated waters. Hence, we propose here that the oxygen deficiency associated surfacing of fishes would be much more along NT as compared to ST (Figure 9). Certainly, more dedicated and long-term effort based on the field measurements is required to validate this hypothesis.

In complete RDA, the major hydrographical parameters (salinity, temperature, nitrate, silicate, phosphate and turbidity) together described 49.2- 53.3% of the overall variance of the biological components. In partial RDA salinity, 49 % of the total variation in biological parameters was explained by salinity alone, which also indicate the predominant role of the KBW influx in structuring the biological variability in the study region. The unexplainable percentage variations in biological parameters by RDA could be partly attributed to the biological factors such as growth and grazing etc. The general interrelationship of the environmental and biological variables are presented in RDA Triplot. In Triplot, locations are displayed by green circles, and environmental and biological variables are denoted by solid red and blue arrows, respectively (Figure 10). The direction of a parameter arrow indicates their increasing gradient, and the angle between two parameter arrows represents how closely they are correlated. The temporal shift in the hydrographical parameters and

their influence in plankton distribution was well-reflected in the RDA Triplot. The increasing gradients of turbidity and nutrients and decreasing gradients of salinity along the observations of S1, S2 and S3 indicate the influence of riverine flux. The microplankton abundance arrow was oriented in the left-hand side of the plot where higher gradients of salinity, total and microplankton chlorophyll a were found along the northern transects (N1, N2). The abundance of pico and nanoplankton was positively linked to the low salinity and high turbidity indicating their linkage to the estuarine influx (Figure 10).

4. Conclusion

The inhibition of upwelling by freshwater in the coastal waters of Kochi along the southwest coast of India during the SWM and its variation over a short spatial scale are presented in this study. Two cross-shore transects were studied based on the sampling during the SWM, one at the south (ST) and the other at the north (NT) of the main inlet (Kochi) of the KBW. The freshwater flux and the associated surface layer stratification was found to be more pronounced along ST, which inhibited the upwelling and the surfacing of nutrient-rich oxygen-deficient waters. On the other hand, stratification was weaker in NT, which was only 8 km north of ST. This variation in short spatial scale between ST and NT was caused by the southward advection of the low salinity plume from the Kochi inlet under the influence of the southerly coastal currents. ST was characterized by stronger stratification in the surface layers causing lower phytoplankton biomass compared to NT. The more upwelled nutrients in the surface waters along NT sustained a higher concentration of larger (micro) phytoplankton, whereas, the low saline plume of KBW resulted in the predominance of smaller (nano) phytoplankton. As the low oxygenated upwelled waters were found very close to the surface along NT, there are more likely chances of fishes to concentrate in the surface waters in this region. It is also proposed that this situation may be valid to many similar estuarine inlets along the southwest coast of India depending upon the direction of the coastal currents.

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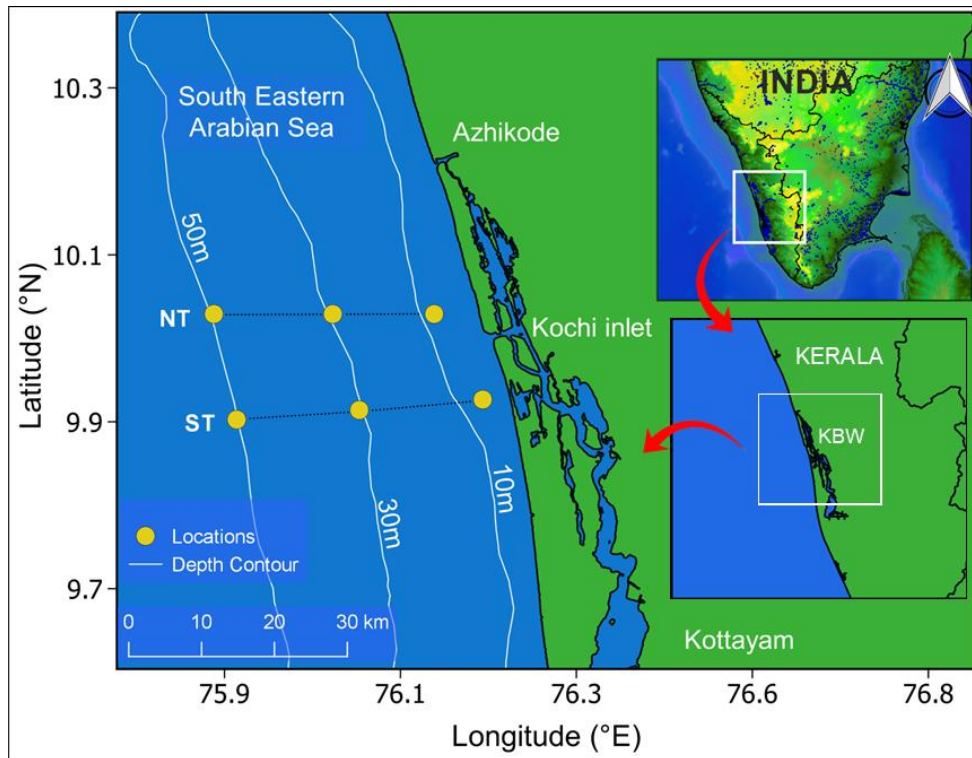


Figure 1 - Study area and sampling locations along the southeastern Arabian Sea. Two cross-shore transects - Northern Transect (NT) and Southern Transect (ST), both located ~8km apart on both sides of the Kochi inlet, were sampled up to a depth of 50m onboard CRV *Sagar Purvi*.

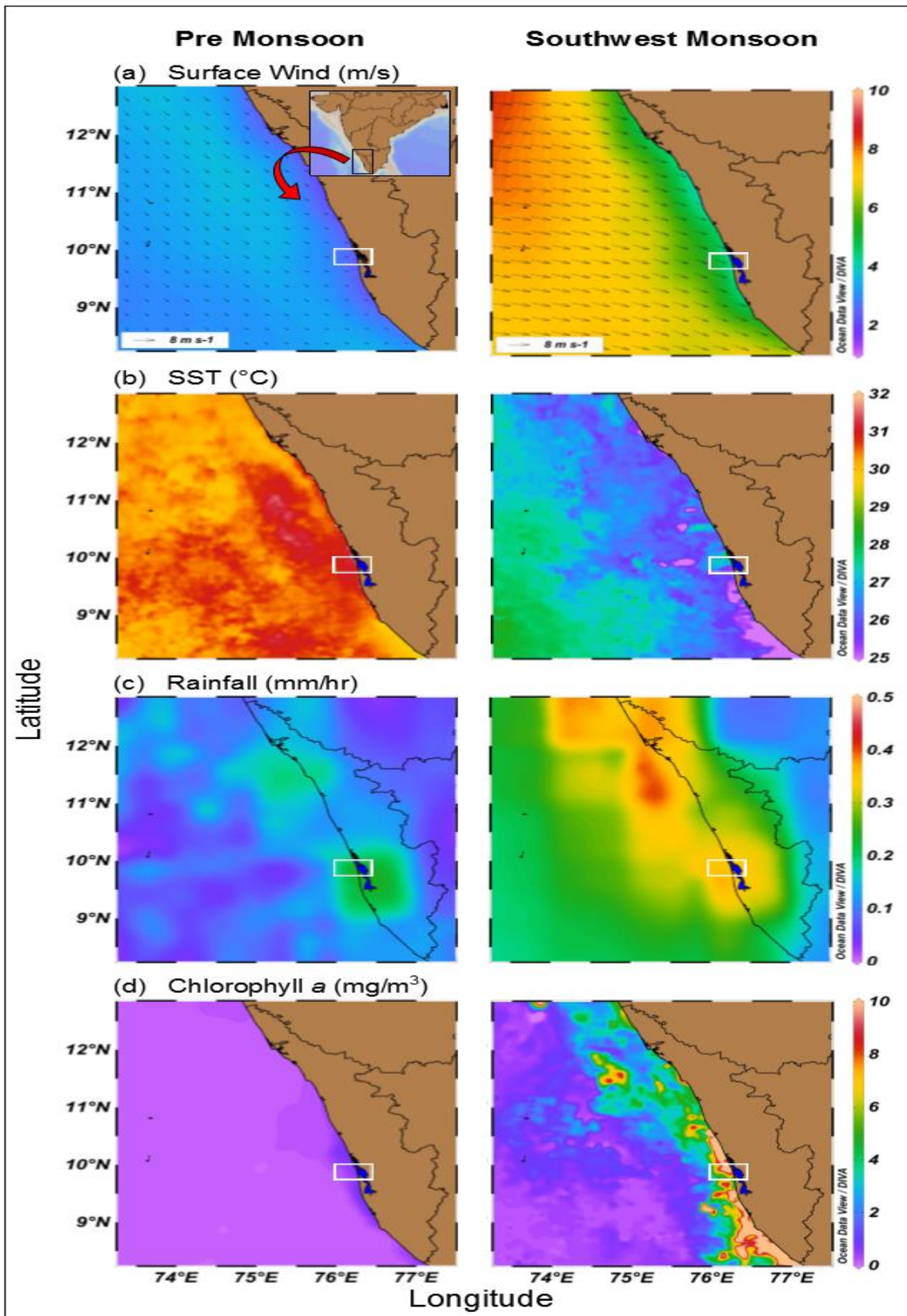


Figure 2 – Seasonal variations of (a) Sea surface wind, (b) sea surface temperature, (c) rainfall and (d) surface phytoplankton biomass (chlorophyll-a) during the Pre-Monsoon (left side panels) and the Southwest Monsoon (right side panels). The white box indicates the present sampling region.

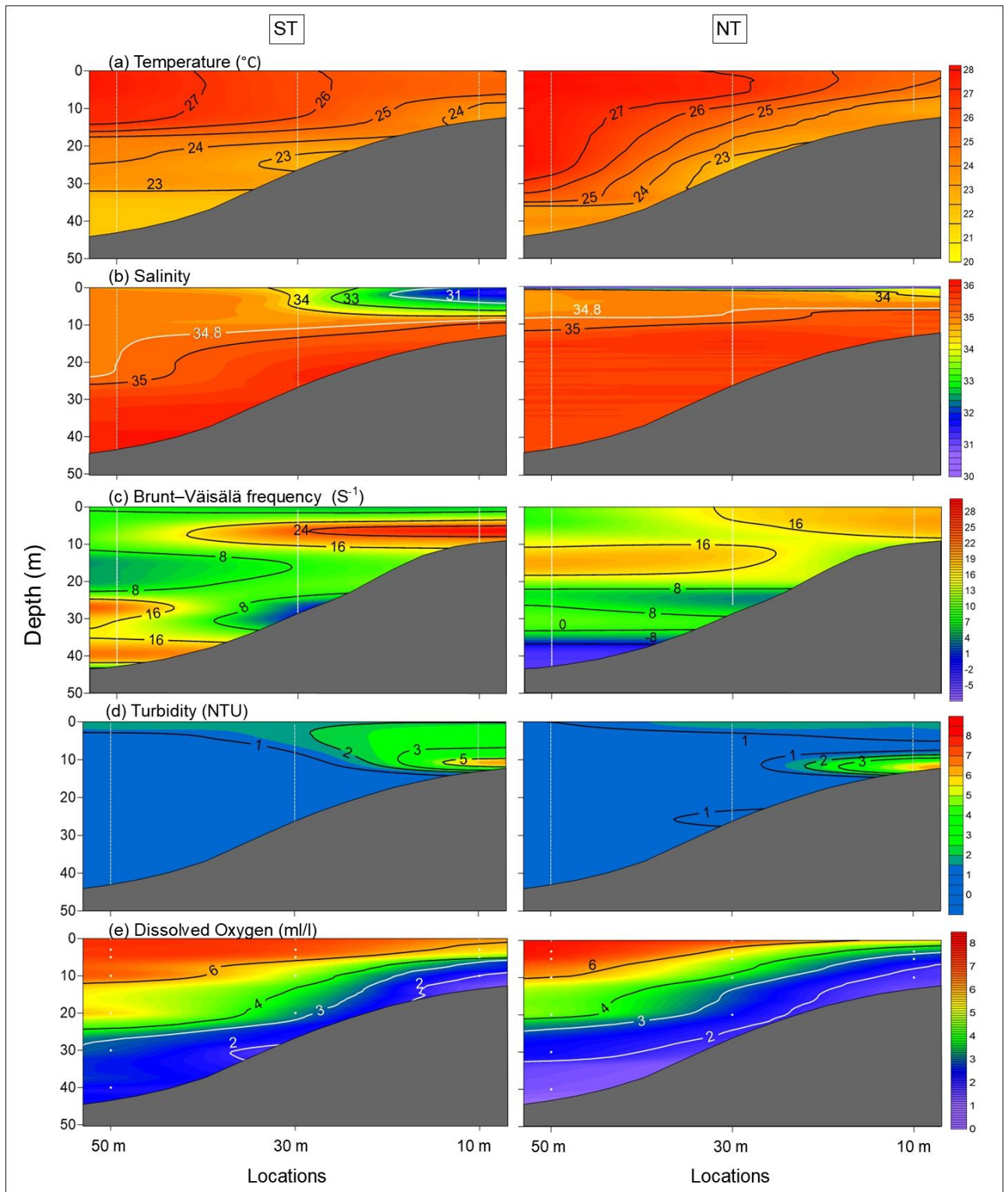


Figure 3 - Cross-shore vertical distribution of temperature, salinity, Brunt Vaisala frequency, turbidity and dissolved oxygen along southern transect (ST) and northern transect (NT) during the Southwest Monsoon.

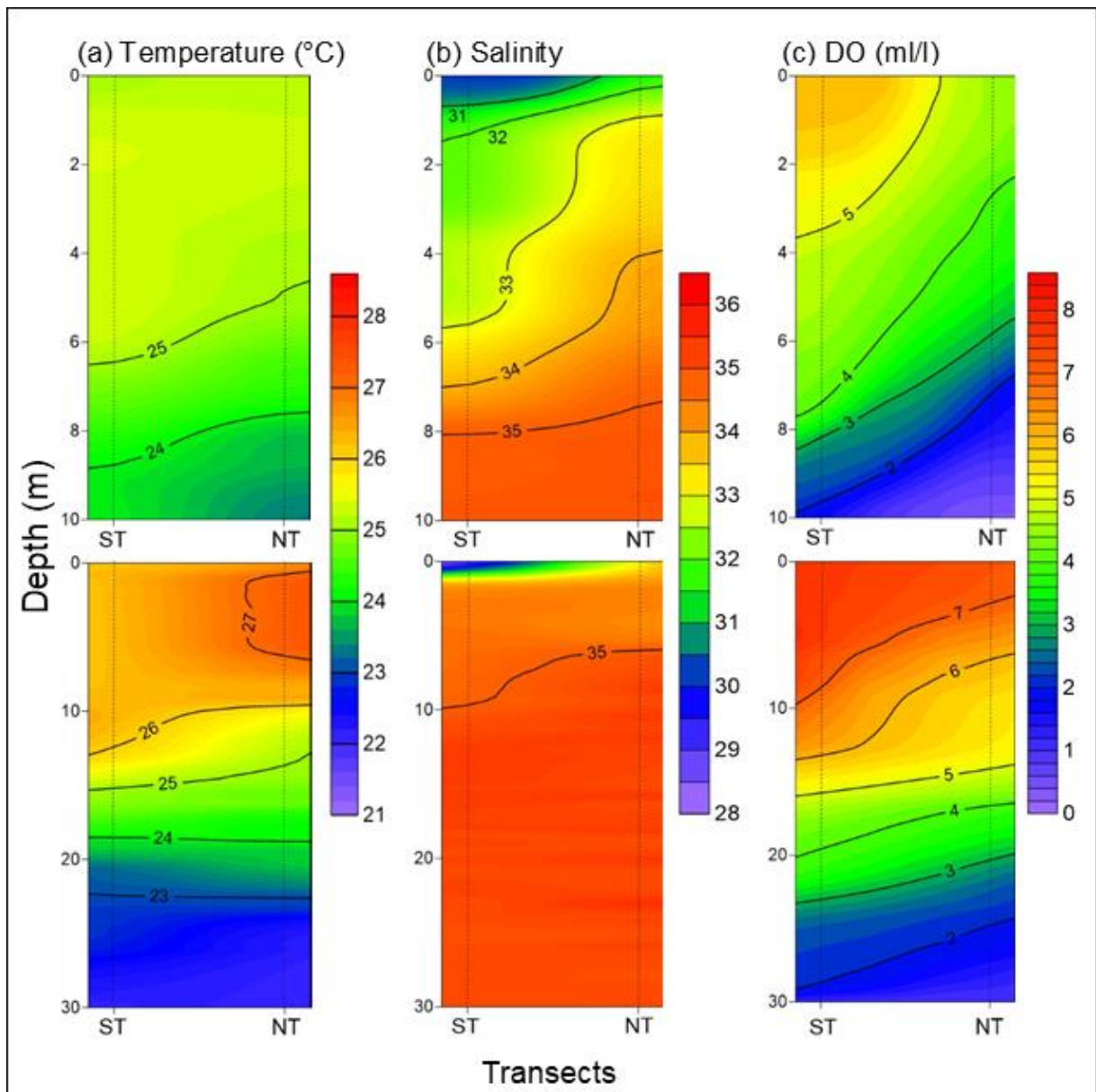


Figure 4 - Along-shore distribution of temperature, salinity and dissolved oxygen along ST and NT. Top panels are 10m location and bottom panels 30m locations.

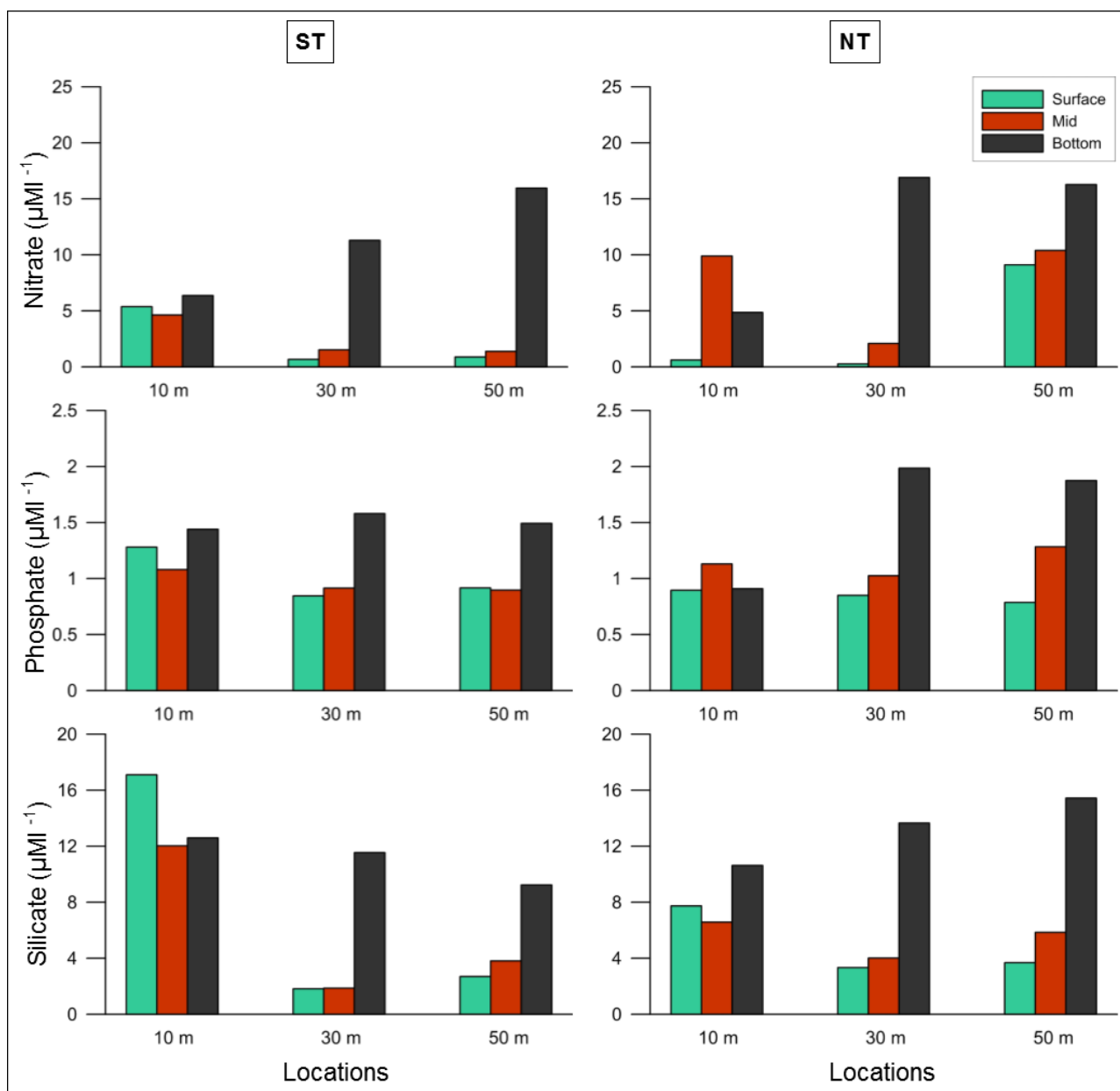


Figure 5 - The distribution of macronutrients (a) nitrate, (b) phosphate and (c) silicate in the water column along ST and NT.

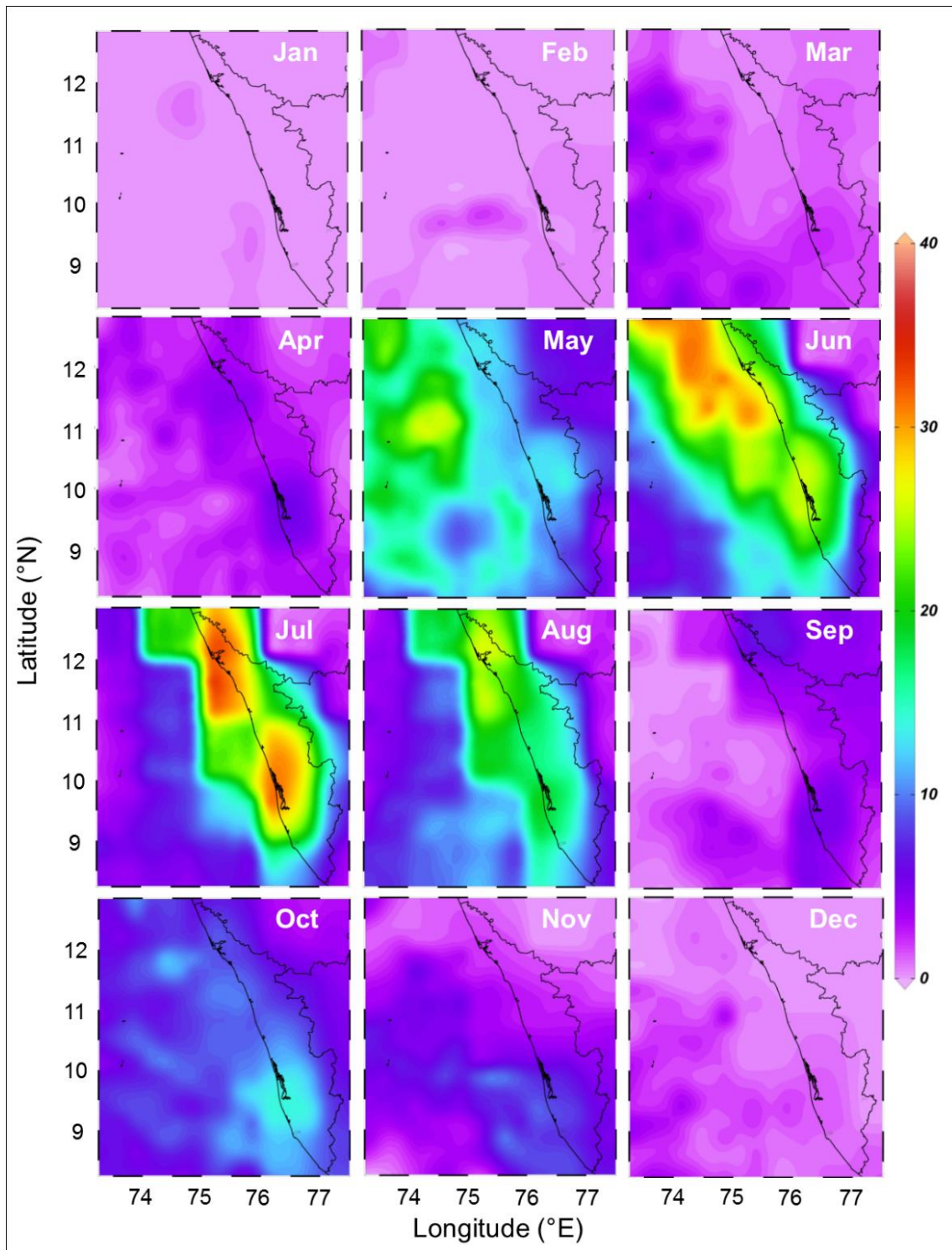


Figure 6 - Monthly variations of rainfall in the study domain. Significantly high rainfall is evident during the Southwest Monsoon period

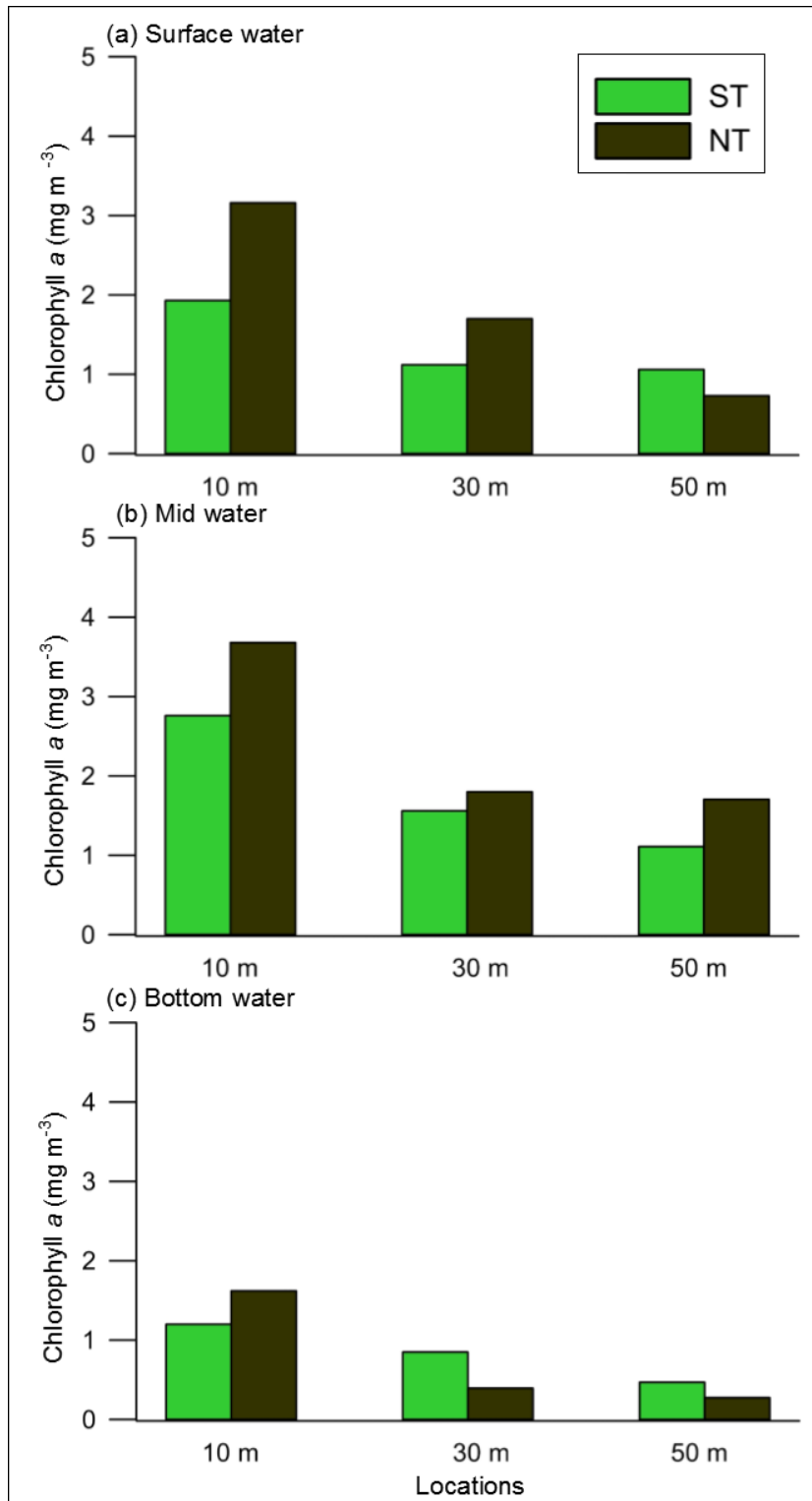


Figure 7 - The distribution of phytoplankton biomass (chlorophyll *a*) in the (a) surface, (b) middle and (c) bottom water along the sampling transects.

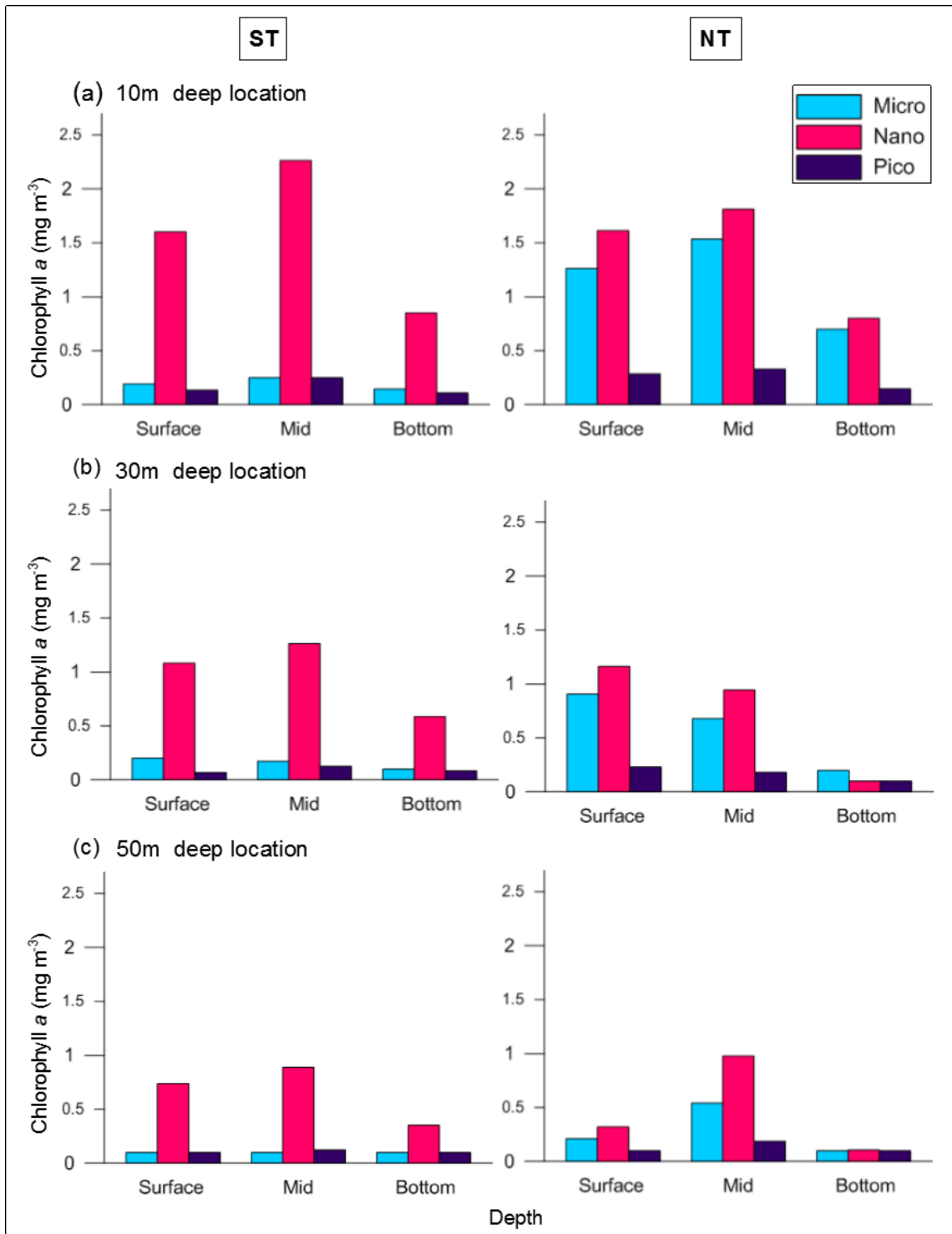


Figure 8 – Phytoplankton size-based chlorophyll-a biomass in the water column at (a) 10m, (b) 30m and (c) 50m locations along ST and NT.

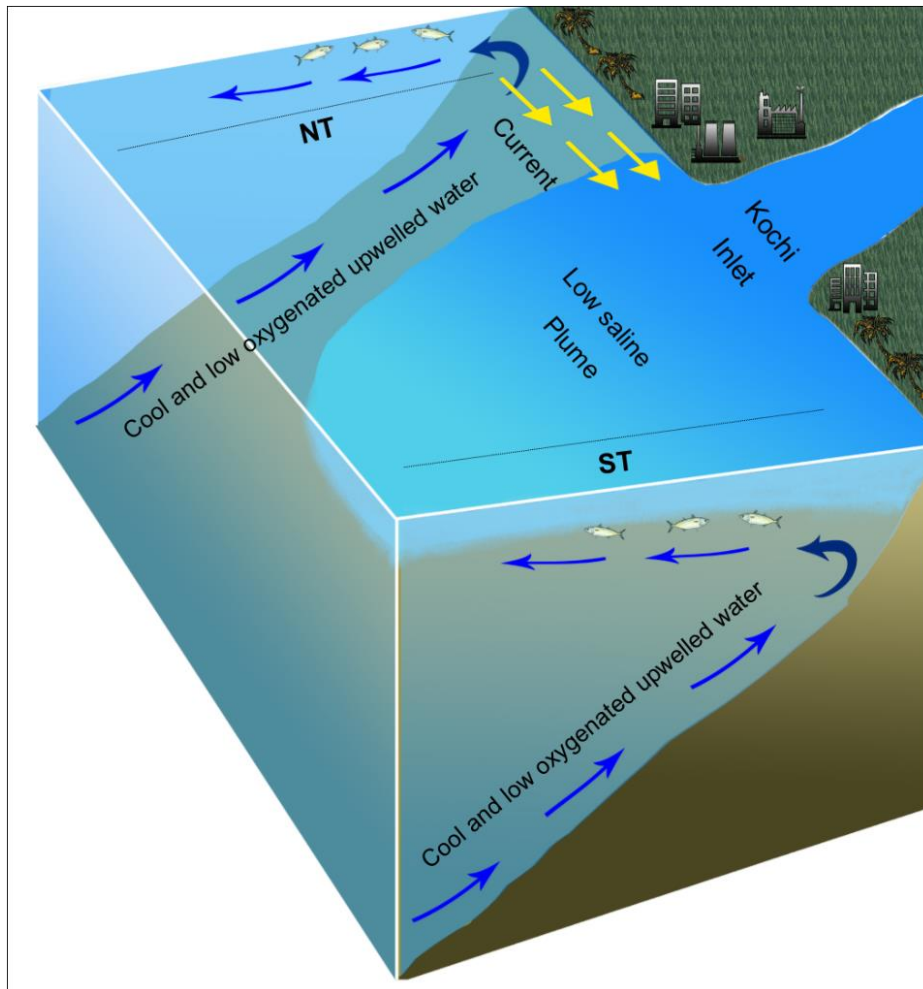


Figure 9 - A schematic diagram showing the inhibition of upwelled water along ST where strong estuarine/freshwater plumes occurs during the Southwest Monsoon. On the other hand, such a low salinity plume is not evident along NT during the Southwest Monsoon resulting in the more active surfacing of oxygen-deficient upwelled waters along this transect.

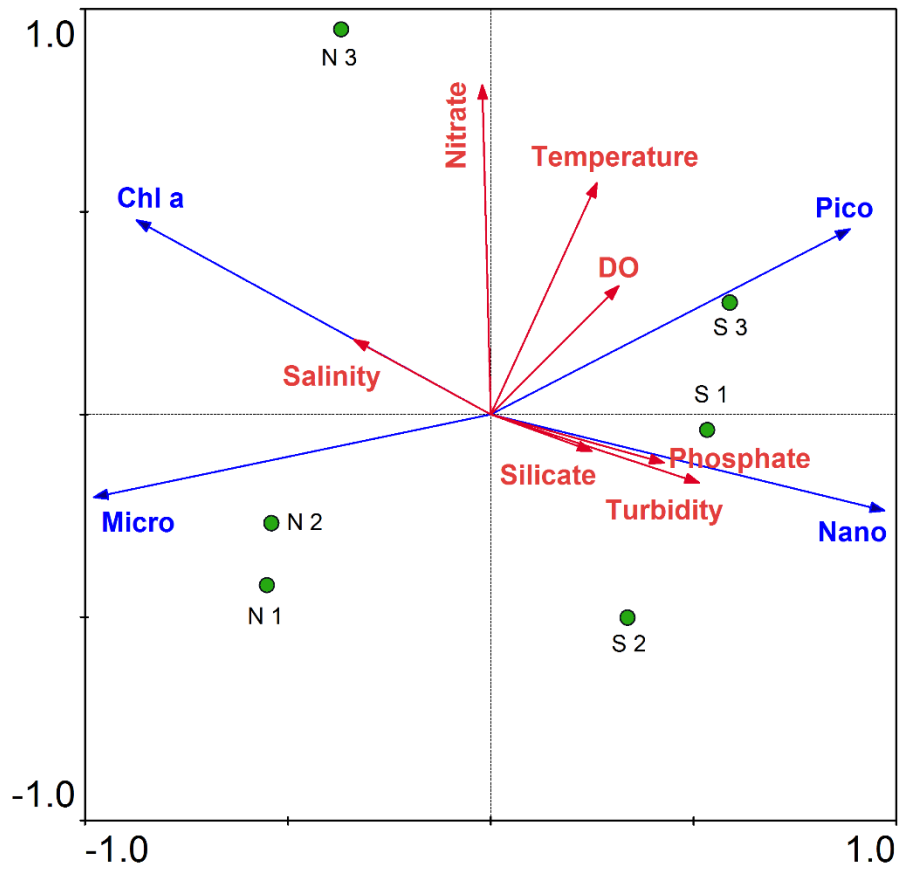


Figure 10 - RDA Triplot showing the overall interrelationship of environmental and biological variables in the study region, Sampling points are marked in green filled circles. Abbreviations: S1 to S3 along ST and N1 to N3 along NT. 1, 2 and 3 indicates the depths 10m, 30m and 50 respectively. Chl a - Chlorophyll-*a*, Micro - Microplankton, Nano - Nanoplankton, Pico - Picoplankton.

Table 1 - Earlier records of inhibition of coastal upwelling by freshwater influx

Salient observations	Reference
In the coastal waters of Kochi, cooler upwelled water was found near the bottom which was not evident in the surface waters due to the dominance of freshwater influx.	Ramamirtham and Jayaraman, 1960
The high freshwater outflow that arising from the river Columbia suppresses the coastal upwelling along the inner shelf of Washington.	Duxbury, 1966, Bowden, 1983, Hickey et al., 2005
The freshwater induced plume along the western Bay of Bengal suppresses coastal upwelling	Shetye et al., 1991
The discharge from Godavari river along the est coast of India forms a low saline plume (50 km) and this inhibits coastal upwelling	Johns et al., 1993
In the strong upwelling regions along the Chesapeake Bay, the high saline bottom water had to restrict it's surfacing for a couple of days for the released buoyant plume to move offshore.	Lentz, 2004
The strong stratification caused by the freshwater influx from the Changjiang river inhibited coastal upwelling in the East China Sea	Tseng et al., 2014
In the coastal waters of Kochi, the upwelled waters were shifted offshore wards (~35km away from shore) due to the hindrance made by the movement of less saline water mass from the Kochi backwaters into the southeastern Arabian Sea.	Gupta et al., 2016
Rising of cooler water was observed during the Southwest Monsoon along the southwest coast of India (off Kochi). But in the inshore waters surfacing of upwelled water was inhibited by low saline water from the Kochi backwaters.	Anjusha et al., 2018
Upwelling could be mediated by the freshets creating a stratified water column in the nearshore waters where it is restricted to the subsurface and probably advect offshore wards under the low saline water column.	Karnan et al., 2020