

## **An appraisal of biological responses and network of environmental interactions in non-mining and mining impacted coastal waters**

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### **Abstract**

The coastal waters of Goa and Ratnagiri lying on the West coast of India are influenced by terrestrial influx. However, Goa is influenced anthropogenically by iron-ore mining while Ratnagiri by deposition of heavy minerals containing iron brought from the hinterlands. We hypothesize that there could be a shift in biological response along with changes in network of interactions between environmental and biological variables in these mining and non-mining impacted regions, lying 160 nmi apart. Biological and environmental parameters were analyzed during pre-monsoon season. Except silicates, the measured parameters were higher at Goa and related significantly, suggesting bacteria centric, detritus-driven region. At Ratnagiri, phytoplankton biomass related positively with silicate suggesting a region dominated by primary producers. This dominance perhaps got reflected as a higher tertiary yield. Thus, even though the regions are geographically proximate, the different biological response could be attributed to the differences in the web of interactions between the measured variables.

### **Keywords:**

Bacteria; Phytoplankton; Coastal Waters; West Coast of India; Mining

## 1. Introduction:

Coastal regions are dynamic, ecologically significant and economically important systems. Complex interactions between the physico-chemical, biological and geological features govern biogeochemical processes in these areas. These interactions are not static but rather dynamic responses to various environmental factors (Cloern 2001). Climatic, oceanic and terrestrial influences such as riverine input, upwelling and anthropogenic activities are widely acknowledged as factors playing an important role in altering these interactions (Xu 1989; Cloern 2001; Pearson and Dawson 2003; Apple et al. 2008). Consequently, trophic conditions and fishery potential of the region are apparently affected (Xua et al. 2004). Moreover, anthropogenic impacts are reported to cause environmental degradation and the rate of degradation depends on the local and regional characteristics (Morales-Ojeda et al. 2010).

The coastal waters of Goa and Ratnagiri along Central West Coast of India form a part of an extensive productive continental shelf. These two regions are geographically proximate lying 160 nmi apart and have independent estuarine systems. The sediments are rich in extractable minerals. The physical characteristics of both sites are given in Table 1. The notable differences between the two regions are the type of minerals present in the sediment and the extent of anthropogenic influences on these two areas. Goa has significant deposits of haematite ( $\text{Fe}_2\text{O}_3$ ) followed by negligible amount of magnetite ( $\text{Fe}_3\text{O}_4$ ), limonite ( $\text{FeO}(\text{OH}) \cdot n\text{H}_2\text{O}$ ) and goethite ( $\text{FeO}(\text{OH})$ ) (Kalavampara 2009). The coastal waters are influenced by terrestrial influx through the Mandovi-Zuari estuarine complex especially during monsoon season. Regionally important activities associated with tourism and fishing is supported by these waters. Mining activities in upland watershed areas and spillage during transportation of ferromanganese ores to the harbor have been suggested to significantly increase the nutrient loadings in these waters (De Souza 1999; Algarasamy 2006). These anthropogenic activities especially during the pre-monsoon season were demonstrated to cause iron enrichment which influenced nitrification and sulfate reduction rates consequently affecting carbon mineralization (Krishnan et al. 2007; Krishnan and Loka Bharathi 2009; Attri et al. 2011). Moreover, nutrient loadings are further enhanced by inputs from associated mangrove swamps, domestic sewage and industrial effluents (Qasim and Sen Gupta 1981; Satyanarayana et al. 1996; Algarasamy 2006; Sardesai and Sundar 2007; Nagvenkar and Ramaiah 2009). This could possibly lead to increased primary productivity in the region. In contrast, the Ratnagiri waters are less impacted by industrial and urban pollution (Ingole et al. 2009; Table 1). Additionally, the sediments are rich in placer

minerals such as ilmenite ( $\text{FeTiO}_3$ ) and magnetite ( $\text{Fe}_3\text{O}_4$ ) (Siddiquie and Rajamanickam 1979). Bio-available iron released from these minerals is perhaps involved in enhancing regional primary productivity subsequently enhancing the tertiary productivity of the area (Fernandes et al. 2011; Department of Fisheries, Government of Maharashtra, India, <http://fisheries.adfmaharashtra.in>).

Thus, the coastal waters off Goa represents mining impacted while off Ratnagiri represent non-mining impacted waters. The present work is focused to compare some of the notable interactions in these mining and non-mining impacted coastal areas. In this paper, we have tried to identify consequences of these well studied pressures on the functioning of the associated coastal waters. Thus, assuming that the pressure is derived from their respective sources at each site, this paper attempts to describe the environmental-biological “network of interactions” in mining and non-mining impacted coastal waters. Here, the term “network of interactions” refers to the web of statistically significant interlinkages between different biotic variables.

## **2. Materials and methods**

### ***2.1 Study area***

In May 2008, two cruises were undertaken onboard CRV *Sagar Sukti* in coastal Arabian Sea along the Central West Coast of India. The study consisted of two transects perpendicular to the coast, extending from near-shore to offshore with a maximum water depth of 100 m (Fig. 1). Transect 1 was off Ratnagiri coast (RAT) and comprised of five stations between  $17^\circ 02' 33''\text{N}$ ,  $73^\circ 13' 26''\text{E}$  and  $17^\circ 02' 29''\text{N}$ ,  $72^\circ 8' 18''\text{E}$ . Transect 2 was off Goa coast (GOA) and comprised of six stations located between  $15^\circ 29' 56''\text{N}$ ,  $73^\circ 42' 14''\text{E}$  and  $15^\circ 30' 00''\text{N}$ ,  $73^\circ 02' 55''\text{E}$  (suppl. Table 1). At both transects, nearshore stations represented at stations at water depth of  $<30\text{m}$  while offshore stations represented stations  $>30\text{m}$ .

### ***2.2 Sample collection and processing***

At each sampling station, continuous vertical profiles of temperature and salinity were obtained using a CTD SeaBird Electronic 25 cast. Water sampling for estimating chemical and biological parameters was done at pre-selected discrete depths with 5 L Niskin bottles. All the sub-sampling collection bottles for nutrients were acid (1 M HCl) washed, rinsed with Milli-Q water (resistance  $18.3 \Omega$ ) and dried before use.

### ***2.3 Chemical analyses***

Dissolved oxygen (DO) were analyzed using Winkler's titrimetric method (Strickland and Parsons 1965) and Metrohm 785 DMP Titrino, with potentiometric endpoint detection (sd  $\pm 0.07\%$ ). Nutrients such as Nitrate ( $\text{NO}_3^-$ -N), Nitrite ( $\text{NO}_2^-$ -N), Phosphate ( $\text{PO}_4^{3-}$ -P) and Silicate ( $\text{SiO}_4^{2-}$ -Si) were analyzed using Technicon TACS (Model AA2) autoanalyzer (Wurl 2009). Freshly prepared calibration standards were used.

### ***2.4 Biological analyses***

ATP was extracted as detailed in Holm-Hansen and Booth (1966) and the concentration was measured with a luminometer (BMG Labtech Luminometer, Lumistar Optima). Total bacterial counts (TC), Total viable-aerobic counts (TVa) and Total viable-anaerobic counts (TVan) were estimated as described by Hobbie et al. (1977), Kogure et al. (1979) and Loka Bharathi et al., (1999), respectively by epifluorescence microscopy (Nikon 50i, Nikon, Tokyo, Japan). Bacterial carbon biomass was estimated assuming that one bacterial cell contains 15 fg of carbon (Fagerbakke et al. 1996). Chlorophyll a (CHL) and Phaeophytin (Phaeo) were measured according to Yentsch and Menzel (1963) using a fluorometer (Turner Designs, USA, 7200). Phytoplankton cells (size  $\geq 5 \mu\text{m}$ ) was quantified and identified after fixing with Lugol's iodine (1% w/v). Sedgwick-Rafter chamber on an inverted microscope (Olympus IX51, Tokyo, Japan) was used for enumeration and the cells were identified according to Tomas (1997). Estimates of primary productivity (PP) rates was according to JGOFS Report No. 6, (1990) using the light and dark bottle method. One ampoule of  $\text{NaH}^{14}\text{CO}_3$  (Board of Radiation and Isotope Technology, Mumbai; Specific activity 185 kBq) was added to each 300 ml polycarbonate bottle (Nalgene, Germany). The incubation time at both the locations was same and the bottles were incubated on the deck for 12 hours from dawn to dusk. Radioactivity was measured using a liquid scintillation counter (Beckman Coulter, USA, Model LS6500). The unit of productivity has been given in  $\text{mgC}/\text{m}^2/\text{day}$  integrated to 15m nearshore and 50m offshore at both the locations.

### ***2.5 Statistical analyses***

Bacterial and phytoplankton abundance data were  $\log(x+1)$  transformed. Analysis of variance (ANOVA) was done to determine significant differences between sites. Pearson's correlation analysis to decipher interrelationships between the environmental and biological parameters was done using Statistica version 6.0. For comprehensible representations, only relationships corrected for Bonferroni

( $p \leq 0.002$ ,  $\alpha = 0.05$ ) were illustrated in the network using MS Visual Basic. Principal component analyses (PCA) were performed using XLstat version 2012 after normalization by correlation matrix.

### 3. Results

#### 3.1 Physico-chemical parameters at the two transects, GOA and RAT

Vertical profiles of temperature, salinity, DO and nutrients at each transect are shown in figure 2 and the mean values of near-shore and offshore stations are given in table 2. Temperature exhibited strong vertical gradient and was  $\sim 3\%$  higher at near-shore stations off GOA. Besides, the sea surface temperature (SST) at both the locations was found to be nearly  $30^\circ\text{C}$  (Fig. 2a, b). Vertical profiles of salinity showed little difference between the two stations (Fig. 2c, d). DO vertical profiles showed that the surface layers were more oxygenated and values decreased significantly with depth at GOA ( $r = -0.600$ ) and RAT ( $r = -0.511$ ) (Fig. 2e, f). The offshore RAT waters had relatively high mean concentrations of DO at  $4.19(\pm 0.96)$  ml/l. All the nutrient parameters decreased with increasing distance from the coast (Fig. 2). The offshore GOA stations had high mean concentration of  $\text{NO}_3^-$ -N at  $4.01(\pm 3.35)$   $\mu\text{M}$ . The overall mean concentration of  $\text{NO}_3^-$ -N at GOA was  $\sim 13\%$  higher than RAT (Table 2). In contrast,  $\text{NO}_2^-$ -N concentration at GOA was much lower offshore than near-shore stations and ranged from non detectable levels to  $0.77$   $\mu\text{M}$  (Fig. 2j). Further, the overall mean concentration was  $37\%$  lower than RAT (Table 2). At GOA, the  $\text{PO}_4^{3-}$ -P concentration ranged between  $1.5$ – $4.5$   $\mu\text{M}$  and was higher at the near-shore stations, compared to the offshore (Fig. 2l, Table 2). Besides, the overall mean concentration was  $61\%$  higher ( $p \leq 0.001$ ) than RAT. In contrast, the  $\text{SiO}_4^{2-}$ -Si levels were low at GOA and ranged between  $0.02$ – $7.7$   $\mu\text{M}$  as compared to  $0.7$ – $20.2$   $\mu\text{M}$  range in RAT waters (Fig. 2m,n). Furthermore, the near-shore RAT water had high mean concentration at  $5.83(\pm 7.2)$   $\mu\text{M}$ , wherein the bottom waters recorded concentration  $> 16$   $\mu\text{M}$  (Fig. 2m, Table 2). Both, GOA and RAT waters recorded high  $\text{PO}_4^{3-}$ -P and  $\text{SiO}_4^{2-}$ -Si concentrations at the deeper depths.

#### 3.2 Biotic variables

##### 3.2.1 Microbial living biomass - ATP

The ATP concentration decreased significantly with increasing distance from the coast at both transects and ranged between  $20$ – $25$   $\mu\text{g/l}$  and  $11$ – $26$   $\mu\text{g/l}$  at RAT and GOA, respectively (Fig. 3a, b). The mean ATP concentration of  $22.61 (\pm 0.94)$   $\mu\text{g/l}$  at RAT was  $\sim 16\%$  higher than at GOA (Table 2).

### 3.2.2 Bacterial components

The abundance of bacteria varied drastically between the two studied locations (Fig. 3). TC varied from  $0.9 \times 10^9$  to  $1.9 \times 10^9$  cells/l at GOA with near-shore waters having numerically higher mean than the open sea (Fig. 3c, Table 2). Besides, the abundance was almost one order higher than RAT. Thus, the converted bacterial carbon biomass at GOA was  $\sim 60 \mu\text{gC/l}$  and was nearly 84% higher than RAT. Following the trend in the TC distribution, the mean TVa population at GOA was nearly an order higher at near-shore stations compared to the offshore waters (Table 2). However, the TVa abundance at  $10^7$  cells/l was almost an order lower than RAT during the same period (Fig. 3 e,f). In contrast, the TVan population at both the study areas was in the order of  $10^7$  cells/l, with marginally higher mean abundance at GOA (Fig. 3 g,h, Table 2).

### 3.2.3 Phytoplankton components

Spatially, the phytoplankton components in near-shore waters at both sites were high compared to open sea and followed the general pattern of other variables (Fig. 4). Significant differences were found in the CHL and Phaeo concentrations between the two sites, GOA and RAT ( $p \leq 0.006$ , one way ANOVA, Table 2). CHL concentration was in the range  $0.07\text{--}14.8 \mu\text{g/l}$  at GOA and  $0.06\text{--}4.3 \mu\text{g/l}$  at RAT (Fig. 4 a,b). The mean concentration at near-shore GOA station was high at  $7.47 \pm 3.21 \mu\text{g/l}$  (Table 2). A high value of  $> 13 \mu\text{g/l}$  was recorded at station 1 of GOA. Overall, GOA had  $\sim 79\%$  higher CHL concentration than RAT. Likewise, Phaeo concentrations followed a trend similar to CHL with near-shore stations recording high mean concentration at  $2.14 (\pm 0.74) \mu\text{g/l}$  (Fig. 4 c,d, Table 2). Consequently, the average CHL-Phaeo ratio at GOA was 3.5 and 2.8 near-shore and offshore, respectively. Correspondingly at RAT, the ratio was 4.0 and 3.1. The PP values varied over a large range and the highest primary production ( $449 \text{ mgC m}^{-2} \text{ d}^{-1}$ ) was recorded at the surficial layer of the near-shore station at GOA. Besides, the overall PP value at GOA was  $\sim 82\%$  higher than RAT. The abundance of phytoplankton was in the similar range at GOA ( $0.08\text{--}14.88 \times 10^3$  cells/l) and RAT ( $0.08\text{--}16.72 \times 10^3$  cells/l), respectively (Fig. 4 g,h). High mean abundance was recorded at near-shore stations (Table 2). Accordingly, the calculated mean specific phytoplankton production i.e. PP:CHL was 14.7 and 28.4 at GOA near-shore and offshore, respectively. At RAT, the ratio was lower at 11.2 and 19.8. In GOA, the abundance of diatom ranged  $0\text{--}13.92 \times 10^3$  cells/l, while dinoflagellates ranged between  $0\text{--}1.04 \times 10^3$  cells/l (Fig. 4 j,l). Correspondingly in RAT, it was  $0\text{--}16 \times 10^3$  cells/l and  $0.064 \times 10^3$  cells/l, respectively (Fig. 4 i,k). Diatoms dominated the microphytoplankton composition at

~85% and ~95% at GOA and RAT, respectively (Table 3). Among the diatoms, the pennate forms comprised nearly 55 and 61% off GOA and RAT, respectively. *Nitzschia* was the dominant genus followed by *Synedra* and *Navicula* at both the locations.

### 3.3 Statistical analysis

ANOVA showed that there were significant differences between the variables of the two transects (ANOVA;  $F=13.9$ ,  $p=0.0002$ ) especially biotic variables (Table 2). Pearson's correlation analysis, revealed that the increasing distance from the coast negatively regulated TVa, ATP, CHL, Phaeo, Phytoplankton, PP and diatoms in GOA (Table 4a) and ATP and phytoplankton in RAT (Table 4b). Some of the notable significant interrelationships at  $p\leq 0.001$  in GOA were PP with CHL ( $r=0.682$ ), and  $\text{SiO}_4^{2-}$ -Si distribution with TC ( $r=0.439$ ).  $\text{NO}_2^-$ -N positively correlated with TC, TVa, ATP, CHL, Phaeo and PP ( $p>0.002-\leq 0.05$ , Table 2). CHL coupled positively with TVa ( $r=0.533$ ) and ATP ( $r=0.777$ ), DO linked positively with temperature ( $r=0.564$ ), and negatively with TVan ( $r=-0.393$ ). At RAT, the CHL related positively to  $\text{SiO}_4^{2-}$ -Si and ATP to nitrate ( $r=0.59$ ) and phytoplankton ( $r=0.43$ ).

In Goa, PCA analysis showed that about 81% of the data variability was explained using five composite variables (Table 5). Using 25 m isobath as a reference, PCA plots exhibited clear demarcation of near-shore and offshore cluster (Fig. 5). The plots revealed that the projection of points separated samples from GOA into two major groups on principal component (PC) 1. The positive side constituted stations belonging to  $\leq 25\text{m}$  isobaths and negative to  $\geq 50\text{m}$  isobaths (Fig. 5a). Environmental variables closely associated with biotic variables on the ordination diagram were  $\text{NO}_2^-$ -N with ATP and phytoplankton components,  $\text{SiO}_4^{2-}$ -Si with TVan. PC1 explaining 36% of the total variance, had high positive factor loadings for abiotic variables such as depth, temperature, salinity and  $\text{NO}_3^-$ -N ( $\geq 0.5$ ). Biotic variables included TVa, ATP and the phytoplankton components. PC2 explained 19% of the variation and PC3 12%. In contrast, the PCA plot in RAT exhibited three clusters of sampling depths which overlapped with each other (Fig. 5b). Results demonstrated that  $\text{NO}_3^-$ -N was closely associated with phytoplankton and diatom,  $\text{SiO}_4^{2-}$ -Si with Phaeo and CHL, salinity and  $\text{PO}_4^{3-}$ -P with TVan. PC1 of RAT was dominated by depth and temperature. PC2 which explained 21% was dominated by  $\text{SiO}_4^{2-}$ -Si and DO. PC3 which explained 15% of the variation was dominated by salinity.

## 4. Discussion

### 4.1. Similarities between the two study sites

#### 4.1.1 Physical forcings on coastal water during the study period

In the present study, there was no homogenization of the water mass since a stratified water column was developed due to negative temperature gradient. The presence of  $>30^{\circ}\text{C}$  SST precluded upwelling (Fig. 2). During March-May, the prevalent wind speed of  $\sim 5$  m/s is unable to break the stratification caused by high SST formed due to incoming shortwave radiation (Kumar and Narvekar 2005). Additionally, during May-September, the direction of West India Coastal Current (WICC) is equatorwards along the Indian West Coast. Circulation in the upper Indian Ocean is reversed seasonally as a consequence of reversing wind direction over North of  $10^{\circ}\text{S}$ . The wind blows from Southwest during May-September and from Northeast during November-February (Luis and Kawamura 2004 and references therein). Moreover, the currents are driven by local winds having periods  $<10$  days (Shetye et al. 2008). Taking into account the above discussion, it is possible that there is perhaps movement from anthropogenically less impacted RAT waters (Table 1) to GOA during the sampling season. Thus, even though the two transects are 160 nmi apart, the ecological functioning of RAT apparently is possibly less subject to physical forcings such as currents from GOA during the study period.

#### 4.1.2. Influence of terrestrial influx on coastal water during the study period

The influence of river inflows was evident as penetration of less saline waters into the coastal waters. Besides, chemical and biotic variables especially phytoplankton components were significantly high at near-shore stations (Fig. 2,3,4, Table 2). At both transects, the deeper waters are enriched with nutrients. Nutrient profiles showed that  $\text{NO}_3^-$ -N and  $\text{NO}_2^-$ -N were more riverine and  $\text{SiO}_4^{2-}$ -Si and  $\text{PO}_4^{3-}$ -P were more coastal and benthic. Reasons for nutrient enrichment at deeper depths include diffusion flow from deeper layers, sedimentation/remineralisation of autotrophic organic matter and re-suspension of fine-grained, organic sediments by the strong tidal currents (Liu et al. 2003; Santos et al. 2008). Another similarity between the two sites is phytoplankton assemblage. *Nitzschia* dominated followed by *Synedra* and *Navicula*. Moreover, all the above species are pennate forms and have a higher surface to volume ratio than centrics and can absorb nutrients rapidly (Paul et al. 2008). These forms comprised  $\sim 55\%$  in GOA and  $61\%$  in RAT (Table 3). Dominance of pennates has



been demonstrated during pre- and post-monsoon in other Indian coastal waters, (Chandran et al. 1985; De et al., 1994, Paul et al. 2007; Sahu et al. 2012).

#### ***4.2. Dissimilarities between the two study sites***

The results clearly indicated that the sites were different. PCA plot of GOA strongly demonstrated that the near-shore and offshore clusters were more distinctly separated by 25 m isobaths perhaps suggesting the extent of influence of the associated estuary on coastal waters. However, in RAT, an overlap of the three clusters formed, suggested subtle gradation in the waters from near-shore to offshore. Also, topology plots of Pearson's correlation between the variables revealed that the interrelationships were higher in number in GOA than RAT emphasizing the higher complexity of the region off GOA, than off RAT (suppl. Fig. 1).

##### ***4.2.1. Cascading influence of nutrient input on biotic variables***

The phytoplankton components such as abundance, CHL, Phaeo and PP were ~10%, 79%, 80% and 82% higher in GOA than RAT (Table 2). Higher productivity is possibly triggered by nearly 13% and 61% higher  $\text{NO}_3^-$ -N and  $\text{PO}_4^{3-}$ -P concentrations in GOA. Such signatures have been previously reported in various coastal waters and ascribed to nutrient input through riverine and sewage discharge (Xu 1989; Cloern 2001; Apple et al. 2008; Morales-Ojeda et al. 2010). In GOA, terrestrial inputs such as litter-fall from ~18 sq.km mangrove swamps, and anthropogenic activities such as sewage discharge and mining in upland watershed areas of Mandovi-Zuari estuarine system, could contribute to increased input of  $\text{NO}_3^-$ -N,  $\text{PO}_4^{3-}$ -P and iron in coastal waters (De Souza et al. 1981; Qasim and Sengupta 1981; De Souza 1999; Sardesai and Sundar 2007; Nagvenkar and Ramaiah 2009). This possibly could lead to higher primary productivity than RAT. The enrichment in iron is evident especially during the pre-monsoon season and is attributed to activities such as spillage during transportation of ferromanganese ores (De Souza 1999; Alagarasamy 2006; Krishnan et al. 2007; Attri et al. 2011). In Goa, the iron concentration was 22-497 mg/g and 0.1-44 mg/l in sediment and water, respectively (Kamat and Sankaranarayanan 1975; Alagarasamy 2006, Mesquita and Kaisary 2007). This range especially in the sediments was comparatively higher than other Indian coastal regions (Alagarasamy 2006). In contrast, the associated mangroves of RAT cover a mere 8.28 sq.km while the total iron is the range of 50-149 mg/g and ~10 mg/l in sediment and water, respectively (Table 1; Rokade 2009; Fernandes 2011). Therefore, the total sedimentary iron concentration is 3-4 times higher in GOA than RAT. Availability of iron in the water column is

largely dependent on the pH and organic carbon concentrations of the water. As GOA waters are higher in organic carbon loading perhaps leading to a relatively lower pH, the bio-availability of iron in the form of ferrous could be correspondingly higher. Thus, it is possible that high phytoplankton biomass and productivity in GOA could be triggered by the cumulative effect of increased input of nutrients and iron. Besides, as the concentrations of nitrate at both locations are almost same, it is probable that the higher productivity at GOA may not be totally attributed to  $\text{NO}_3^-$ -N but to also other nutrient like  $\text{PO}_4^{3-}$ -P. The concentration of  $\text{PO}_4^{3-}$ -P is many times (61%) more at GOA, probably due to higher loading of organic carbon and total iron. These two factors facilitate the release of  $\text{PO}_4^{3-}$ -P. Therefore it is suggested that for the higher productivity at GOA,  $\text{PO}_4^{3-}$ -P could have a more prominent role in these waters than off RAT.

However, higher PP did not synchronize with the oxygen availability in GOA. DO was marginally lower than RAT (Table 2) indicating a deficit in DO concentration. Generally, high productivity and high oxygen levels relate during the initial phase of phytoplankton proliferation. However, during the subsequent phases when bacteria multiply, the primary productivity relates less with oxygen levels. The 12% lower CHL:Phaeo ratio than RAT phytoplankton at GOA indicates that the phytoplankton were relatively more senescent. Further, our data on higher bacterial abundance and viability off Goa suggests the possibility of bacterial multiplication. Enhancement of productivity could lead to eutrophication and suboxia where most organic matter gets channeled through microbial loop triggering higher bacterial load. Such triggering is clearly evident in TC abundance in GOA which was ~85% higher than RAT. Earlier study in this area has suggested bacterial production exceeds primary production and that the organic matter from adjacent estuary supported heterotrophy in coastal systems (Pradeep Ram et al. 2003). Further, other studies have shown that net heterotrophy dominate during Spring Intermonsoon (March-May) in the Arabian Sea (Ramaiah et al 1996; Pomroy and Joint, 1999; Robinson and Williams, 1999; Sarma et al 2003; Sarma 2009). Thus, it could imply that anaerobes are involved in the organic matter degradation furthering our inference that fixed carbon could be channeled through the microbial loop under hypoxic conditions. Moreover, even though TVan contributed to <1% of TC forming only 0.3% at GOA and 0.6% at RAT, the TVan population at  $0.46(\pm 0.13) \times 10^7$  cells/l was relatively 69% higher in GOA than RAT. Also, TVan and DO related negatively ( $r=-0.393$ ) indicating the preference of anaerobic conditions by this community of bacteria. In contrast, TVa contribution to TC was only 0.65% in GOA unlike RAT where it was 81%. The similar order in abundance in TC and TVa at  $10^8$  cells/l in RAT was indicative of higher

viability of aerobic bacterial community. This feature has been earlier recorded in the adjoining beach sediments and bay waters (Fernandes 2012).

The variation in the nutrient concentrations brought about changes in the relative abundance of diatoms and dinoflagellates. In the present study, diatoms dominated the microphytoplankton composition by ~85% and 95% in GOA and RAT, respectively. Consequently, the diatom:dinoflagellate ratio is only 5 at GOA and 15 at RAT. It is suggested that this difference in the ratio could have a noticeable effect on the nutrient cycling, food web structure and energy flow (Officer and Ryther 1980; Michaels and Silver 1988; Legendre and Le Fevre 1989). Diatoms are involved in the transfer of energy to higher trophic levels while flagellates get entrained into the 'microbial food web' (Azam et al. 1983; Doering et al. 1989; Legendre and Le Fevre 1989). This difference is particularly reflected in the abundance and distribution of TVa and TVan. In GOA, both TVa and TVan were about two orders less than TC ( $10^9$  cells/l). These are plausibly grazed by dinoflagellates, whose abundance is nearly 10% of total phytoplankton in GOA. Such inference has been drawn from other systems which indicate that cells that are actively growing and dividing are usually large (Krambeck and Krambeck 1984) and protozoans selectively graze on faster growing cells (Krambeck 1988; Gonzalez et al. 1990; Sherr et al. 1992; Seong et al. 2006; Jeong et al. 2008).

#### ***4.2.2. Interrelationships show RAT is less heterotrophic than GOA***

Less heterotrophic conditions in RAT are further confirmed by interrelationships between CHL and  $\text{SiO}_4^{2-}\text{-Si}$ . CHL related positively to  $\text{SiO}_4^{2-}\text{-Si}$  in RAT (Table 4b), suggesting active participation by siliceous diatoms and silicoflagellates. Consequently, Phaeo also related significantly to silicate (Table 4b) corroborating the dominance of diatoms in the phytoplankton community (Table 2). In contrast, in GOA, the  $\text{SiO}_4^{2-}\text{-Si}$  distribution correlated with TC suggesting a significant contribution from silicate solubilizing bacteria. This relationship is ascribed to the release of Si by bacterial action from biogenic sources like sinking dead diatoms (Roubeix et al. 2008). However, the average  $\text{SiO}_4^{2-}\text{-Si}$  was 105% lower in GOA compared to RAT (Table 2) perhaps due to the higher rate of utilization by diatoms than replenishment by bacterial solubilisation.  $\text{NO}_2^-\text{-N}$  was 37% lower than RAT and positively correlated to TC, TVa, ATP, CHL, Phaeo and PP ( $p > 0.002 \leq 0.05$ , Table 2). The low nitrite concentration synchronized with low oxygen concentrations. The involvement of  $\text{NO}_2^-\text{-N}$  in multiple processes through bacteria and phytoplankton suggests a dynamic region with higher turnover and tighter coupling between biotic and abiotic parameters. The low Chl:Phaeo ratio in this

region suggested that the phytoplankton could be more senescent leading to higher rate of nitrification. However, we cannot validate this inference of nitrification due to lack of data on ammonia concentrations in these waters.

Thus, the complexity of the coastal area off Goa is apparent from the relationships between the abiotic and biotic parameters. CHL relates with TVa and ATP confirming dependence of bacteria on phytoplankton exudates (Bird and Kalff 1984; Vrede et al. 1999; Jugnia et al. 2007). Aerobic respirers are known to respond rapidly to leaching of DOC from phytoplankton detritus (Kristensen et al. 1995). According to Bukaveckas et al. (2002), a predominance of heterotrophic activity drives a net consumption of organic carbon, net mineralization of C, N and P and a detritivore-based food web. Moreover, under anaerobic conditions and  $\text{NO}_2^-$ -N based associations, as in the present study, net mineralization is dominated by detritus based food web (Kirchman 1994; Hall Jr. and Meyer 1998; Pomroy et al. 2007). Higher productivity and phytoplankton abundance thus may not translate as efficiently to the tertiary level as more of the energy is channeled through bacterial subsystems. Thus, the web of interactions highlights the complexity off Goa (suppl. Fig. 1).

#### ***4.2.2. Principal Component Analysis support relatively more heterotrophic conditions in GOA***

The PCA highlighted the contrast between the two regions. In GOA, environmental variables like  $\text{NO}_2^-$ -N associated with ATP and phytoplankton components while  $\text{SiO}_4^{2-}$ -Si with TVan. This suggests the contribution of phytoplankton to ATP and nitrite and the anaerobes towards silicate solubilizations. DO displayed positive loads on PC2 emphasizing its DO gradient in controlling nutrient concentrations and biological productivity. Such interrelationship has been demonstrated in waters off Gulf of Aqaba (Manasrah et al. 2006) and is mainly attributed to two concurrently occurring processes. Higher light intensity is accompanied by a higher photosynthetic rate in the upper water column (Wheeler et al. 2003) and a lower photosynthetic rate is accompanied by organic matter decomposition in the deeper water column. Furthermore, a negative linear correlation observed between DO and TVan ( $r=-0.393$ ) is suggestive of contribution from anaerobic degradation of organic matter. PC3 explained 12% of the variability and was positively loaded for  $\text{NO}_2^-$ -N and TC indicating that this PC was  $\text{NO}_2^-$ -N enrichment component. In the aquatic environment,  $\text{NO}_2^-$ -N is formed when nitrifying bacteria oxidize  $\text{NH}_4^+$  to  $\text{NO}_2^-$ -N consequently converting  $\text{NO}_2^-$ -N to  $\text{NO}_3^-$ -N (Lewis et al. 1986) or through denitrification where  $\text{NO}_3^-$ -N is reduced to  $\text{NO}_2^-$ -N (Boyd, 1995). Off GOA, the turnover rate of  $\text{NO}_2^-$ -N and  $\text{NH}_4^+$  is high. Previous study in this area has shown that  $\text{NO}_2^-$ -

N production rates were closely related to ammonium production rates. Ammonium and  $\text{NO}_2^-$ -N regeneration rates were among the highest known from near-shore waters (Dham et al, 2002).

Unlike in GOA, where 81% of the data variability was explained using five composite variables, in RAT, the same extent of variability was represented by six PCs (Table 5).  $\text{NO}_3^-$ -N was closely associated with phytoplankton and diatom on the ordination plot, explaining the productivity in this. Association of  $\text{SiO}_4^{2-}$ -Si with Phaeo and CHL and  $\text{PO}_4^{3-}$ -P with TVan possibly indicates that silicate contribute to diatom abundance while anaerobes could possibly influence the availability of phosphate.

Thus, relationships suggest that GOA is relatively more influenced by bacteria while RAT is more influenced by phytoplankton. Taken together the above observations indicate three salient findings when comparing GOA and RAT. Off Goa 1) the network of interactions suggests that the region could be more complex. 2) Bacteria especially anaerobes have a more prominent role 3) The response of biological parameters is relatively more heterotrophic. Thus, we infer that since the natural and anthropogenic pressures in both regions are different, it leads to differences in the topology of interactions: simpler off Ratnagiri and more complex off Goa.

## **5. Conclusion**

Though both the stations are on the Central West Coast of India and <160 nmi apart, the ecological response to the environmental forcings dominated by the respective estuarine systems is distinctly different. Both the locations exhibited varying chemical and biological properties and showed marked variation in their complexities. Ratnagiri has a simpler system dominated by primary producers possibly due to lower but continuous input of nutrients such as nitrate, phosphate and iron into the region. In contrast, the coastal system off Goa is more complex, dominated by intermittent bulk input of nutrients due to mining. Heterotrophic bacteria dominate the detritus based food web in this region. Thus, the water characteristics of GOA and RAT indicate that terrestrial influence apparently plays a major role in dictating the health of these coastal waters. Further, the prevalent food chains at Goa may therefore get reflected as lower local yield at the tertiary level than at Ratnagiri. There could be more insights when further studies are done covering these aspects.

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This article is NIO’s contribution No. -----

## **7. Compliance with ethical standards**

Authors whose names appear on the submission has contributed sufficiently to the scientific work and therefore share collective responsibility and accountability for the results. All funding organizations have been duly acknowledged under the “Acknowledgement section”. The authors declare that they have no conflict of interest.

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### Figure Captions:

Fig. 1: Map showing the location of the sampling stations.

Fig. 2: Vertical profiles of temperature, salinity, DO,  $\text{NO}_3^-$ -N,  $\text{NO}_2^-$ -N,  $\text{PO}_4^{3-}$ -P and  $\text{SiO}_3^{2-}$ -Si along GOA and RAT.

Fig. 3: Distribution pattern of ATP and bacterial abundance (TC, TVa and TVan) at GOA and RAT.

Fig. 4: Distribution pattern of CHL, Phaeo, PP, total phytoplankton abundance, diatom and dinoflagellate abundance along GOA and RAT.

Fig. 5: PCA ordination diagrams of sampling units for the abiotic and biotic variables at GOA (a) and RAT (b).

Suppl. Fig. 1: Comparison of the topology of relationships (bonferroni corrected Pearson correlation) between biological and environmental variables at GOA (a) and RAT (b). Red arrows signify positive relationships whereas blue ones indicate negative correlation between variables. r values are embedded over arrows. Solid arrows and broken arrows indicate significant and insignificant relationship, respectively (Goa n=29x3, Ratnagiri n=24x3).

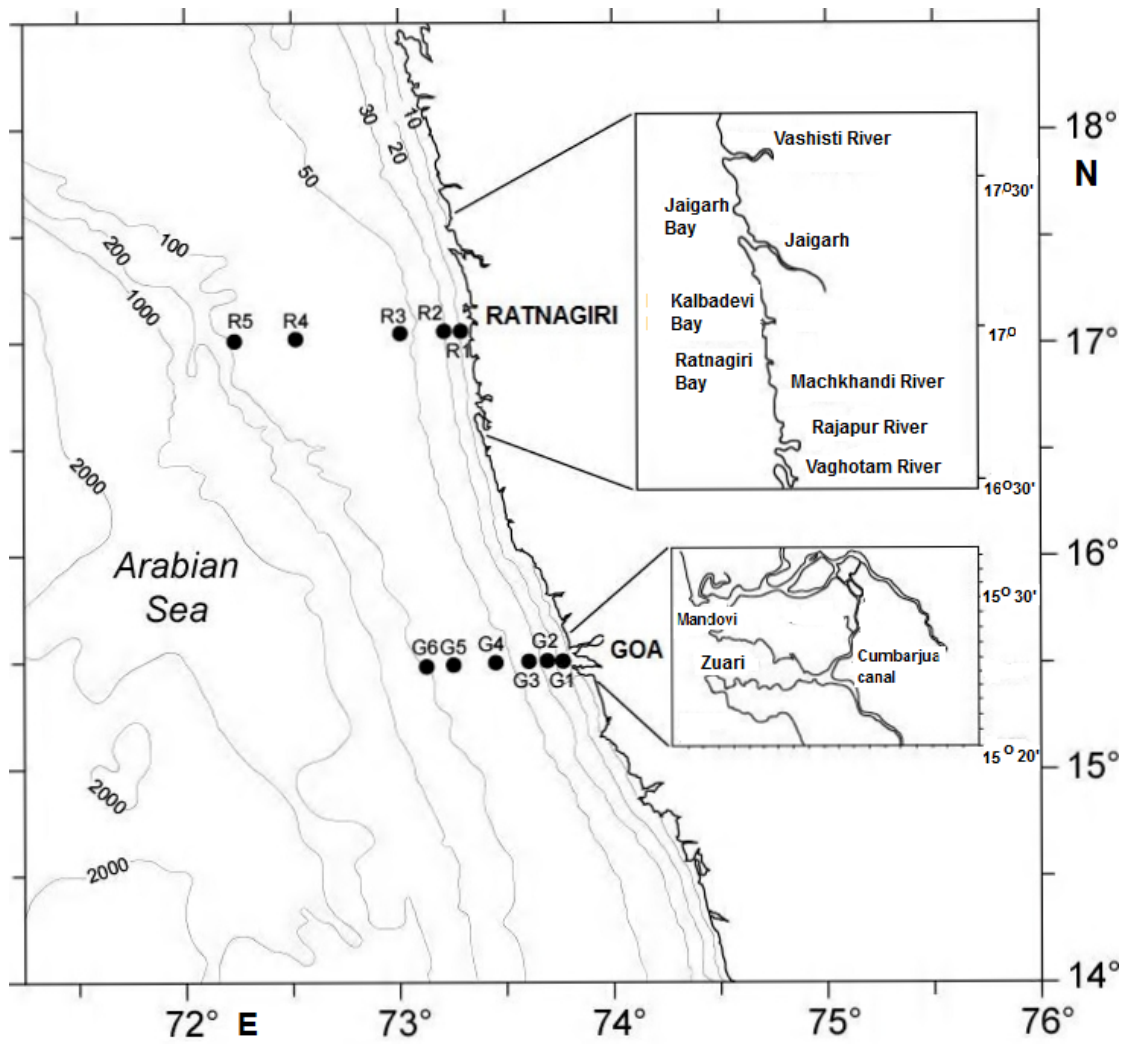


Fig. 1: Map showing the location of the sampling stations.

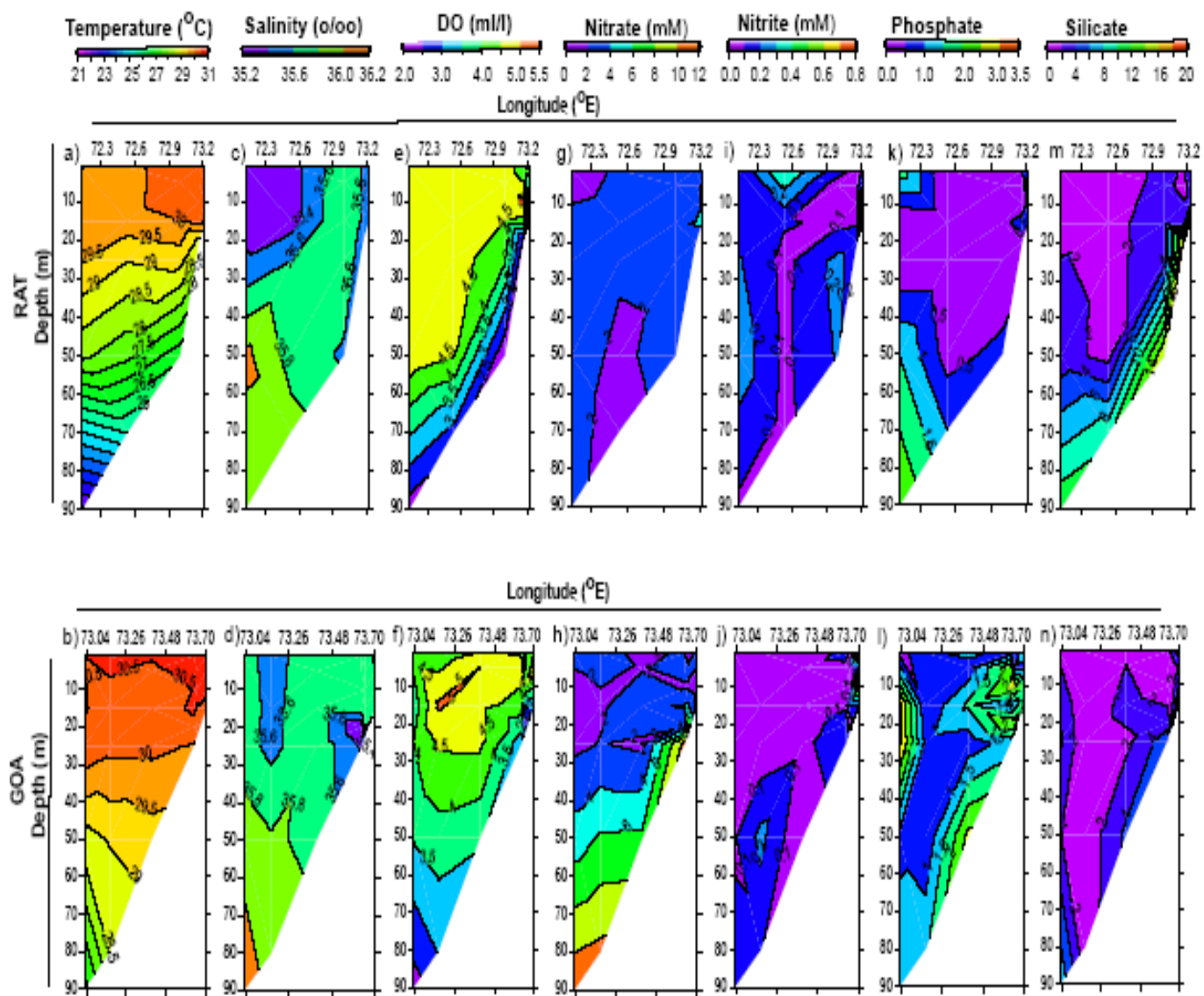


Fig. 2: Vertical profiles of temperature, salinity, DO,  $\text{NO}_3^-$ -N,  $\text{NO}_2^-$ -N,  $\text{PO}_4^{3-}$ -P and  $\text{SiO}_3^{2-}$ -Si along GOA and RAT.

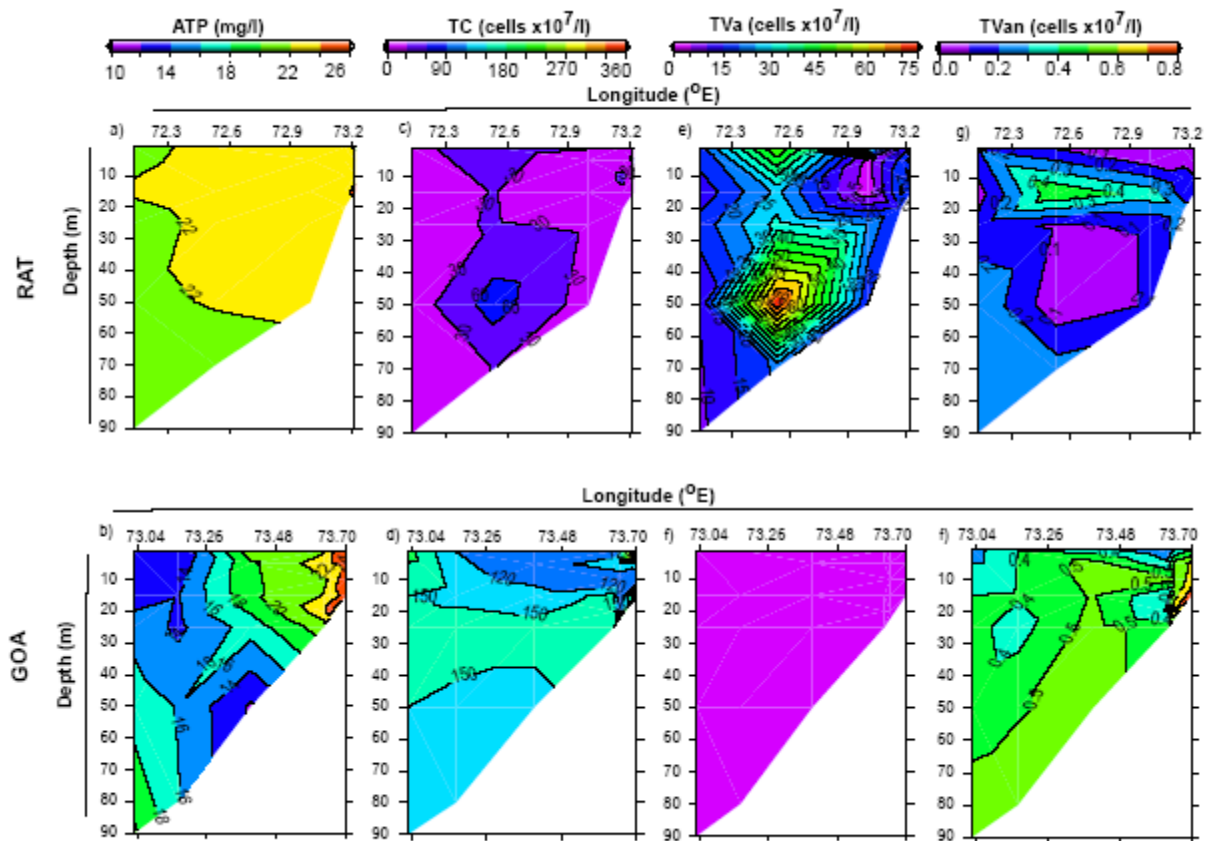


Fig. 3: Distribution pattern of ATP and bacterial abundance (TC, TVa and TVan) at GOA and RAT.

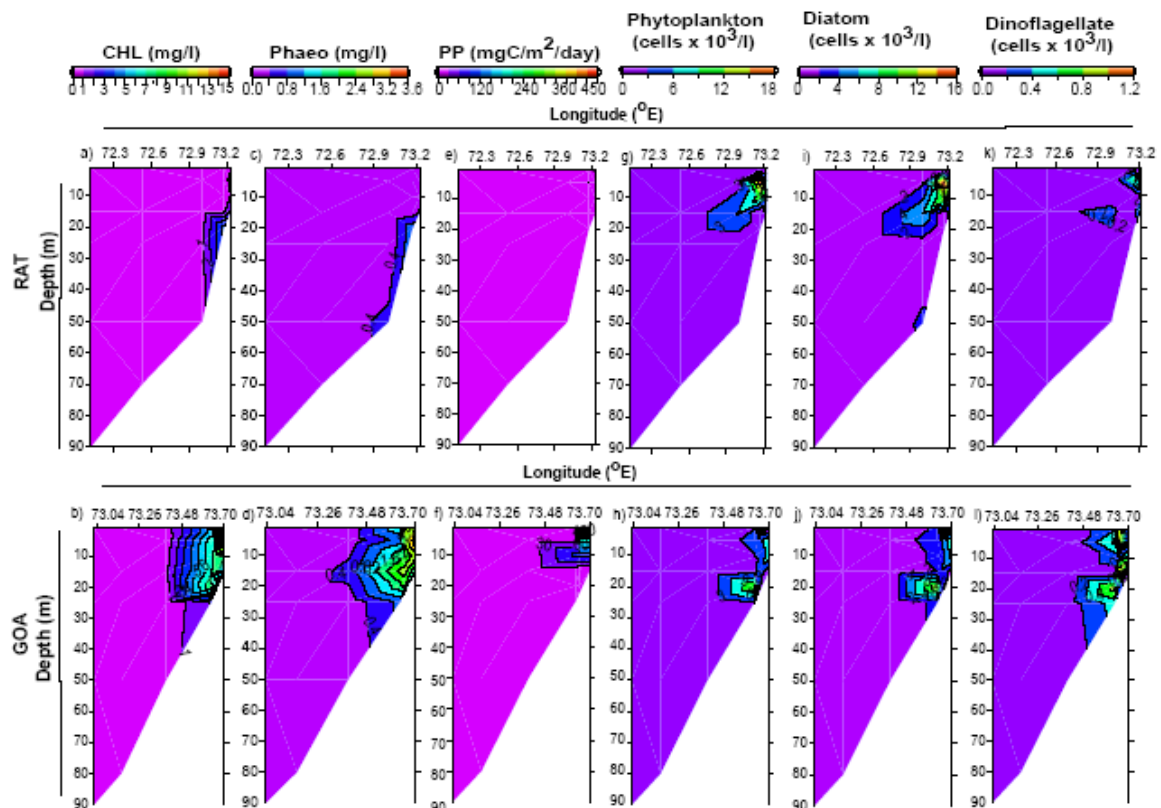


Fig. 4: Distribution pattern of CHL, Phaeo, PP, total phytoplankton abundance, diatom and dinoflagellate abundance along GOA and RAT.

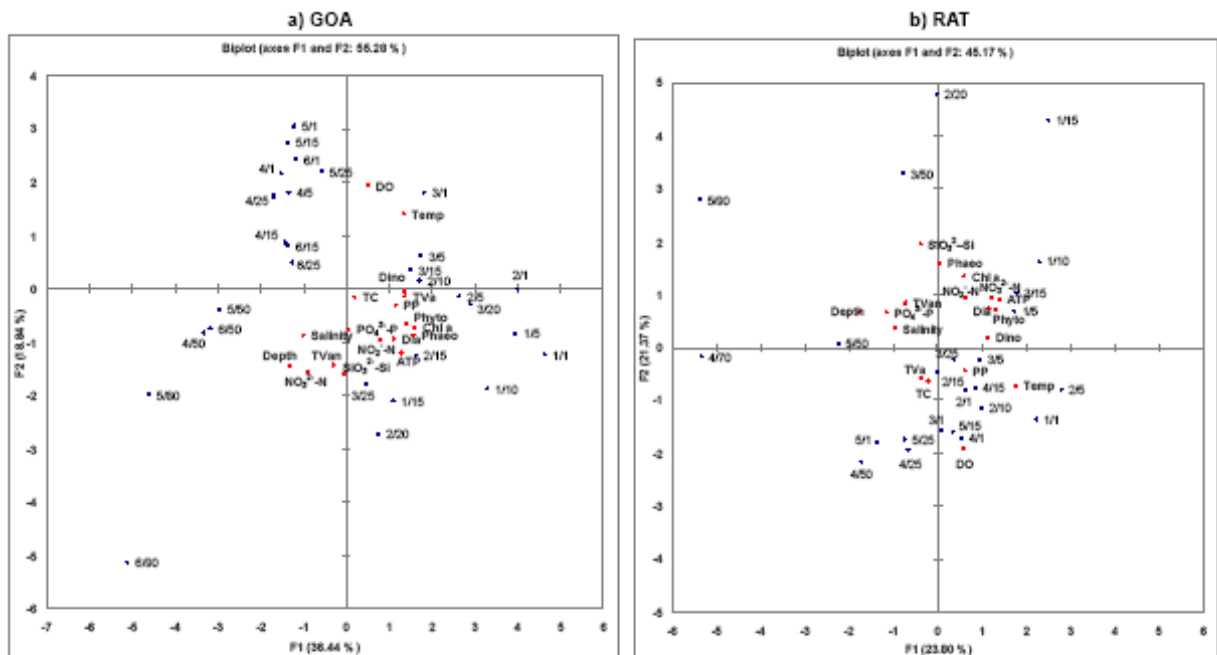


Fig. 5: PCA ordination diagrams of sampling units for the abiotic and biotic variables at GOA (a) and RAT (b).

**Table 1: Characteristics of associated estuarine ecosystems of study areas**

Characteristic	Estuarine system associated with	
	GOA	RAT
Mangrove (Km <sup>2</sup> )	18 <sup>a</sup>	8.28 <sup>b</sup>
Annual precipitation (mm)	2500 - 3000 <sup>a,c</sup>	2600 - 3800 <sup>d</sup>
Discharge rate (m <sup>3</sup> /s)	25 – 175	
Drainage basin area (km <sup>2</sup> )	2553 <sup>a,c</sup>	690 - 2174 <sup>g</sup>
Average runoff (MCM)	5827 <sup>a</sup>	
Inhabitants	~ 1,457,723 <sup>f</sup>	~ 1,612,672 <sup>f</sup>
Waste water discharge/year (m <sup>3</sup> )	5.61 x 10 <sup>6</sup> <sup>a,c</sup>	1.31 x 10 <sup>6</sup> <sup>b</sup>
Industrial organic waste discharge/year (m <sup>3</sup> )		1.1 x 10 <sup>6</sup> <sup>b</sup>
Continental shelf width (km) <sup>i</sup>	94	128
Sediment iron concentration		
Total Fe (mg/g) 22-497 <sup>k</sup>	50-149 <sup>j,l</sup>	
Water iron concentration		
Total Fe (mg/L)	0.08-44 <sup>n</sup>	10.3±1.5

\* Fe – Iron

- a) <http://goaenvis.nic.in>  
b) <http://www.annauniv.edu/iom/iomour/ratnagiri.htm> [http://envis.maharashtra.gov.in/envis\\_data/files/Mdistribution.html](http://envis.maharashtra.gov.in/envis_data/files/Mdistribution.html)  
c) Qasim and Sen Gupta, 1981  
d) [http://cultural.maharashtra.gov.in/english/gazetteer/RATNAGIRI/phy\\_climate.html](http://cultural.maharashtra.gov.in/english/gazetteer/RATNAGIRI/phy_climate.html)  
e) [www.ncw.nic.in/pdfreports/Gender%20Profile-Goa.pdf](http://www.ncw.nic.in/pdfreports/Gender%20Profile-Goa.pdf)  
f) [www.census2011.co.in](http://www.census2011.co.in)  
g) <http://www.hydrology-project.gov.in/surfaceWater.htm>  
h) [ratnagiri.nic.in/distGazette/Part1.pdf](http://ratnagiri.nic.in/distGazette/Part1.pdf)  
i) Rao and Rao (1995)  
j) Rokade, 2009  
k) Alagarsamy, 2006  
l) Fernandes, 2011  
m) Kamat and Sankaranarayanan, 197



**Table 2: The mean concentrations of the physico-chemical and biological parameters studied along with significant ANOVA values between the two transects.**

Parameters (n=9x3)	Goa		Ratnagiri		ANOVA
	nearshore avg(±sd) (n=15x3)	offshore (avg±sd) (n=14x3)	nearshore (avg±sd) (n=15x3)	offshore (avg±sd) (n=53, df=1)	
Temperature (°C)	30.54(±0.23)	29.76(±1.07)	30.15(±0.49)	28.52(±2.33)	ns
Salinity (‰)	35.62(±0.15)	35.75(±0.16)	35.54(±0.04)	35.63(±0.24)	6.3, (p≤0.02)
DO (ml/l)	3.91(±0.75)	4.05(±0.76)	3.84(±0.99)	4.19(±0.96)	ns
NO <sub>3</sub> <sup>-</sup> -N (μM)	3.24(±2.93)	4.01(±3.35)	3.59(±0.66)	2.69(±1.23)	ns
NO <sub>2</sub> <sup>-</sup> -N (μM)	0.19(±0.22)	0.07(±0.06)	0.22(±0.25)	0.15(±0.10)	ns
PO <sub>4</sub> <sup>3-</sup> -P (μM)	1.53(±0.74)	1.32(±0.93)	0.54(±0.43)	0.57(±0.77)	14.9 (p≤0.0003)
SiO <sub>4</sub> <sup>2-</sup> -Si (μM)	2.58(±2.2)	2.2(±2.1)	5.83(±7.20)	3.96(±4.51)	ns
Total Bacterial abundance					
TC (cellsx10 <sup>7</sup> /L)	150(±71)	141(±25)	23(±8)	25(±18)	104 (p≤2x10 <sup>-13</sup> )
TVa (cellsx10 <sup>7</sup> /L)	1.6(±0.4)	0.8(±0.2)	16(±6)	23(±19)	38 (p≤1.54x10 <sup>-7</sup> )
TVan (cellsx10 <sup>7</sup> /L)	0.47(±0.2)	0.45(±0.09)	0.15(±0.12)	0.17(±0.13)	100 (p≤4x10 <sup>-13</sup> )
ATP (μg/L)	23.5(±1.5)	15.9(±3.2)	23(±0.78)	22(±0.87)	ns
CHL (μg/L)	7.47(±3.21)	0.4(±0.2)	1.3(±1.2)	0.36(±0.25)	8.4 (p≤0.006)
Phaeo (μg/L)	2.14(±0.74)	0.13(±0.14)	0.33(±0.38)	0.12(±0.13)	11.3 (p≤0.002)
Phytoplankton abundance					
Total (cellsx10 <sup>3</sup> /L)	5.20(±4.16)	0.21(±0.17)	5.07(±5.66)	0.89(±1.62)	ns
Diatom (cellsx10 <sup>3</sup> /L)	4.66(±3.93)	0.16(±0.16)	4.81(±5.53)	0.82(±1.58)	ns
Dinoflagellate (cellsx10 <sup>3</sup> /L)	0.51(±0.37)	0.09(±0.06)	0.23(±0.23)	0.06(±0.06)	ns
PP (mg C/m <sup>2</sup> /day)	110(±159)	11(±6)	15(±14)	7(±3)	4.7 (p≤0.04)

\* avg: average ns: not significant, values in parantheses are standard deviation (sd)

**Table 3: Percentage composition of the total phytoplankton assemblage at the two transects**

Type	Total phytoplankton (cells/l) Genera Composition	Transect	
		GOA	RAT
		7.58 x10 <sup>4</sup>	5.88 x 10 <sup>4</sup>
		%	%
Diatom	<i>Amphora</i> spp.	0.11	0.00
	<i>Asteromphalus</i> spp.	1.05	2.18
	<i>Asterionellopsis</i> spp.	0.00	0.41
	<i>Actinocyclus</i> spp.	0.74	0.41
	<i>Bacteriastrum</i> spp.	0.21	0.00
	<i>Chaetoceros</i> spp.	1.90	6.53
	<i>Climacosphenia</i> spp.	0.00	0.27
	<i>Coscinodiscus</i> spp.	7.49	2.59
	<i>Hemialus</i> spp.	2.43	1.77
	<i>Hemidiscus</i> spp.	0.21	0.14
	<i>Melosira</i> spp.	2.32	1.77
	<i>Navicula</i> spp.	12.76	9.66
	<i>Nitzschia</i> spp.	21.62	25.31
	<i>Pinnularia</i> spp.	0.53	0.41
	<i>Planktoniella</i> spp.	6.54	2.18
	<i>Pleurosigma</i> spp.	1.90	1.77
	<i>Pseudonitzschia</i> spp.	0.95	0.82
	<i>Rhoicosigma</i> spp.	0.00	0.14
	<i>Rhizosolenia</i> spp.	1.48	4.76
	<i>Synedra</i> spp.	13.61	12.79
	<i>Thalassionema</i> spp.	0.21	7.62
	<i>Thalassiosira</i> spp.	4.32	8.03
	<i>Thalassiothrix</i> spp.	3.69	2.31
	<i>Triceratium</i> spp.	0.84	0.54
Dinoflagellate	<i>Alexandrium</i> spp.	0.11	0.14
	<i>Ceratium</i> spp.	0.32	1.63
	<i>Dinophysis</i> spp.	1.48	0.00
	<i>Dissodinium</i> spp.	0.00	0.27
	<i>Odontella</i> spp.	4.32	1.77
	<i>Oxyphysis</i> spp.	0.00	0.27
	<i>Prorocentrum</i> spp.	4.32	1.50
	<i>Protoperidinium</i> spp.	3.38	1.22
	<i>Proboscia</i> spp.	0.00	0.14
Others	<i>Dictyocha</i> spp.	0.00	0.27
	<i>Eucampia</i> spp.	0.42	0.14
	Unidentified	0.74	0.27

**Table 4: Pearson's correlation table of the two transects**

**a) GOA transect (n=29)**

<b>V</b>	<b>S</b>	<b>D</b>	<b>T</b>	<b>Sal</b>	<b>DO</b>	<b>NO<sub>3</sub></b>	<b>NO<sub>2</sub></b>	<b>P</b>	<b>Si</b>	<b>TC</b>	<b>TVa</b>	<b>TVan</b>	<b>ATP</b>	<b>CHL</b>	<b>Phaeo</b>	<b>Phyto</b>	<b>PP</b>	<b>Dia</b>	<b>Dino</b>
<b>S</b>	1.000																		
<b>D</b>	0.475	1.000																	
<b>T</b>	-0.503	-0.955	1.000																
<b>Sal</b>	0.319	0.567	-0.634	1.000															
<b>DO</b>	-0.050	-0.600	0.564	-0.273	1.000														
<b>NO<sub>3</sub></b>	0.243	0.766	-0.757	0.347	-0.688	1.000													
<b>NO<sub>2</sub></b>	-0.464	-0.085	0.080	-0.131	0.007	-0.044	1.000												
<b>P</b>	-0.059	0.092	0.031	-0.053	-0.283	0.000	0.033	1.000											
<b>Si</b>	-0.109	0.291	-0.325	0.088	-0.420	0.222	0.413	0.400	1.000										
<b>TC</b>	0.031	0.019	0.013	-0.264	0.051	-0.026	0.421	-0.002	0.439	1.000									
<b>TVa</b>	-0.735	-0.536	0.548	-0.502	0.228	-0.372	0.474	0.006	0.247	0.465	1.000								
<b>TVan</b>	-0.260	0.338	-0.302	0.347	-0.393	0.263	0.158	0.201	0.347	-0.136	0.053	1.000							
<b>ATP</b>	-0.849	-0.299	0.268	-0.103	-0.110	-0.074	0.455	0.067	0.220	-0.085	0.533	0.202	1.000						
<b>CHL</b>	-0.847	-0.435	0.458	-0.306	0.099	-0.240	0.526	0.062	0.058	0.088	0.647	0.022	0.777	1.000					
<b>Phaeo</b>	-0.882	-0.415	0.447	-0.264	-0.015	-0.212	0.426	0.004	0.064	-0.041	0.608	0.106	0.820	0.946	1.000				
<b>Phyto</b>	-0.660	-0.376	0.386	-0.376	-0.125	-0.159	0.154	0.051	-0.033	-0.157	0.424	-0.117	0.665	0.732	0.807	1.000			
<b>PP</b>	-0.525	-0.339	0.313	-0.141	0.193	-0.282	0.458	-0.130	0.104	0.289	0.536	-0.054	0.446	0.682	0.612	0.332	1.000		
<b>Dia</b>	-0.560	-0.208	0.217	-0.205	-0.174	-0.033	0.138	0.129	0.069	-0.168	0.240	-0.084	0.643	0.625	0.706	0.881	0.256	1.000	
<b>Dino</b>	-0.529	-0.465	0.538	-0.512	0.016	-0.229	0.177	0.195	-0.163	-0.079	0.522	-0.193	0.460	0.614	0.622	0.718	0.375	0.431	1.000

**b) RAT transect (n=24)**

<b>V</b>	<b>S</b>	<b>D</b>	<b>T</b>	<b>Sal</b>	<b>DO</b>	<b>NO<sub>3</sub></b>	<b>NO<sub>2</sub></b>	<b>P</b>	<b>Si</b>	<b>TC</b>	<b>TVa</b>	<b>TVan</b>	<b>ATP</b>	<b>CHL</b>	<b>Phaeo</b>	<b>Phyto</b>	<b>PP</b>	<b>Dia</b>
	<b>Dino</b>																	
<b>S</b>	1.000																	
<b>D</b>	0.477	1.000																
<b>T</b>	-0.470	-0.949	1.000															
<b>Sal</b>	0.113	0.553	-0.450	1.000														
<b>DO</b>	0.226	-0.511	0.565	-0.112	1.000													
<b>NO<sub>3</sub></b>	-0.528	-0.268	0.295	-0.027	-0.109	1.000												
<b>NO<sub>2</sub></b>	-0.284	-0.114	0.159	-0.176	-0.353	0.302	1.000											
<b>P</b>	0.176	0.497	-0.571	0.319	-0.403	-0.126	-0.017	1.000										
<b>Si</b>	-0.218	0.414	-0.440	0.156	-0.871	0.167	0.392	0.219	1.000									
<b>TC</b>	-0.027	-0.025	0.050	-0.290	0.064	-0.366	0.120	-0.222	-0.098	1.000								
<b>TVa</b>	0.128	0.055	-0.031	-0.272	0.019	-0.361	0.183	-0.192	-0.060	0.937	1.000							
<b>TVan</b>	0.312	0.341	-0.327	0.136	-0.289	-0.028	0.022	0.305	0.253	-0.186	-0.172	1.000						
<b>ATP</b>	-0.639	-0.448	0.460	-0.182	-0.157	0.592	0.331	-0.304	0.174	-0.124	-0.149	0.075	1.000					
<b>CHL</b>	-0.470	-0.207	0.189	-0.247	-0.432	0.275	0.297	-0.183	0.555	0.097	0.036	0.122	0.386	1.000				
<b>Phaeo</b>	-0.234	0.059	-0.096	-0.138	-0.621	0.204	0.189	-0.059	0.754	0.046	0.074	0.147	0.316	0.804	1.000			
<b>Phyto</b>	-0.635	-0.325	0.315	0.011	-0.103	0.428	0.225	-0.037	0.098	-0.289	-0.364	-0.098	0.434	0.121	-0.064	1.000		
<b>PP</b>	-0.099	-0.156	0.149	-0.182	0.222	0.107	0.012	-0.207	-0.046	-0.061	-0.071	-0.338	-0.162	-0.048	-0.201	0.194	1.000	
<b>Dia</b>	-0.490	-0.311	0.242	0.008	-0.095	0.411	0.239	0.022	0.113	-0.294	-0.339	-0.135	0.374	0.135	0.041	0.897	0.107	1.000
<b>Dino</b>	-0.518	-0.220	0.310	-0.210	-0.078	0.419	0.218	-0.239	-0.007	0.054	-0.025	-0.175	0.470	0.062	-0.091	0.393	0.369	0.164
	1.00																	

(V:Variables; S:station; D: Depth; T:temperature; Sal: salinity; DO:dissolved oxygen; NO<sub>3</sub>:Nitrate; NO<sub>2</sub>:Nitrite; P:Phosphate; Si:Silicate; TC: total bacterial counts; TVa: total viable-aerobic counts; TVan: total viable-anaerobic counts; ATP:adenosine triphosphate; CHL: Chlorophyll a; Phaeo:phaeophytin; Phyto: total phytoplankton abundance; PP: Primary productivity; Dia: diatom abundance; Dino: Dinoflagellate abundance)

**Table 5: Factor loading and eigen values of various parameters extracted using principal component analysis.**

Parameter	GOA					RAT					
	F 1	F 2	F 3	F 4	F 5	F1	F 2	F 3	F 4	F 5	F 6
Depth	-0.725	-0.576	-0.012	-0.053	-0.19	-0.844	0.3	-0.12	0.279	0.032	0.163
Temperature	0.742	0.56	0.003	0.167	0.201	0.852	-0.327	0.125	-0.254	-0.052	-0.036
Salinity	-0.563	-0.343	-0.129	-0.472	0.295	-0.452	0.163	-0.504	0.056	-0.088	0.037
DO	0.275	0.774	0.204	-0.255	0.151	0.279	-0.869	-0.158	-0.211	0.017	-0.014
NO <sub>3</sub> <sup>-</sup> -N	-0.504	-0.626	-0.143	-0.022	-0.375	0.59	0.421	-0.232	-0.02	0.055	0.312
NO <sub>2</sub> <sup>-</sup> -N	0.43	-0.383	0.556	-0.182	-0.001	0.302	0.426	0.283	0.315	-0.334	0.061
PO <sub>4</sub> <sup>3-</sup> -P	0.031	-0.302	0.011	0.751	0.39	-0.547	0.295	-0.36	0.137	-0.244	-0.099
SiO <sub>3</sub> <sup>2-</sup> -Si	-0.023	-0.641	0.528	0.293	0.094	-0.183	0.888	0.2	0.145	0.194	-0.079
TC	0.108	-0.062	0.834	0.139	-0.387	-0.094	-0.294	0.804	0.29	-0.276	-0.051
TVa	0.768	-0.056	0.446	0.057	0.027	-0.169	-0.268	0.813	0.301	-0.277	-0.033
TVan	-0.158	-0.568	0.081	-0.103	0.621	-0.344	0.381	-0.098	-0.381	-0.246	0.337
ATP	0.718	-0.479	-0.125	-0.179	0.156	0.674	0.416	0.068	-0.204	-0.241	0.316
CHL	0.889	-0.29	-0.011	-0.178	0.009	0.296	0.611	0.481	-0.252	0.241	-0.172
Phaeo	0.874	-0.346	-0.155	-0.187	0.045	0.026	0.722	0.482	-0.27	0.272	-0.167
Phytoplankton	0.78	-0.264	-0.449	0.094	-0.199	0.625	0.315	-0.43	0.29	-0.235	-0.275
Diatom	0.619	-0.376	-0.463	0.063	-0.176	0.556	0.338	-0.408	0.203	-0.263	-0.475
Dinoflagellate	0.744	-0.02	-0.247	0.274	-0.129	0.55	0.09	0.009	0.475	0.056	0.555
PP	0.639	-0.121	0.311	-0.39	-0.062	0.298	-0.202	-0.108	0.555	0.625	-0.011
Eigenvalue	6.559	3.391	2.18	1.375	1.141	4.285	3.847	2.761	1.487	1.144	1.031
Variability (%)	36.441	18.837	12.113	7.636	6.338	23.803	21.37	15.341	8.261	6.355	5.726

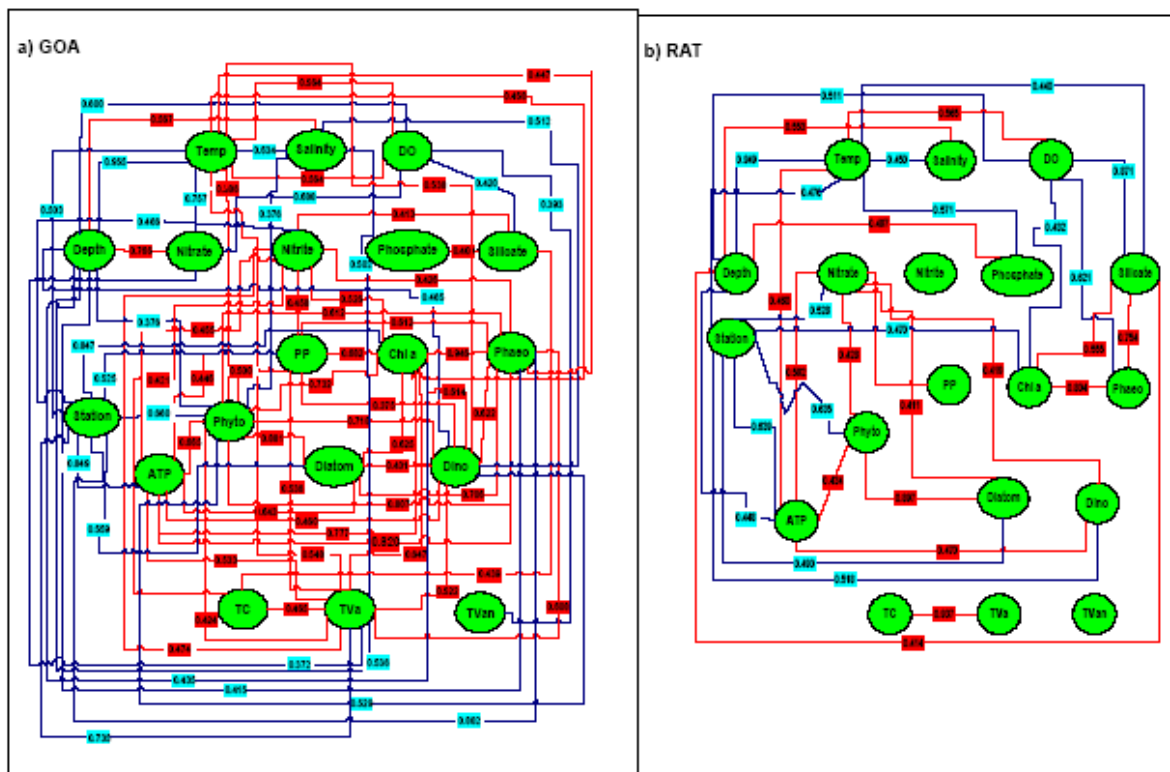
\* F- Factor

**Suppl. Table 1: Location of the stations along the two transects**

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<b>Transect</b>	<b>Station No.</b>	<b>Maximum water depth (m)</b>	<b>Latitude</b>	<b>Longitude</b>
<b>Ratnagiri</b>	1	15	17 <sup>0</sup> 02N	73 <sup>0</sup> 13'E
	2	25	17 <sup>0</sup> 02N	73 <sup>0</sup> 10'E
	3	60	17 <sup>0</sup> 02N	73 <sup>0</sup> 00'E
	4	80	17 <sup>0</sup> 02N	72 <sup>0</sup> 32'E
	5	100	17 <sup>0</sup> 02N	72 <sup>0</sup> 8'E
<b>Goa</b>	1	15	15 <sup>0</sup> 29'56"N	73 <sup>0</sup> 42'E
	2	25	15 <sup>0</sup> 29'58"N	73 <sup>0</sup> 39'E
	3	30	15 <sup>0</sup> 29'50"N	73 <sup>0</sup> 38'E
	4	60	15 <sup>0</sup> 30'00"N	73 <sup>0</sup> 24'E
	5	80	15 <sup>0</sup> 30'00"N	73 <sup>0</sup> 10'E
	6	100	15 <sup>0</sup> 30'00"N	73 <sup>0</sup> 02'E

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Suppl. Fig. 1: Graphical representation of network of relationships (bonferroni corrected Pearson correlation) between biological and environmental variables at GOA (a) and RAT (b). Red arrows signify positive relationships whereas blue ones indicate negative correlation between variables.  $r$  values are embedded over arrows. Solid arrows and broken arrows indicate significant and insignificant relationship, respectively (Goa  $n=29 \times 3$ , Ratnagiri  $n=24 \times 3$ ).