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Variations of physicochemical properties in Kalpakkam coastal waters, east coast of India, during southwest to northeast monsoon transition period

Kamala Kanta Satpathy · Ajit K. Mohanty · Gouri Sahu · Santosh K. Sarkar · Usha Natesan · R. Venkatesan · M. V. R. Prasad

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Abstract A significant variation in physicochemical properties of the Kalpakkam coastal waters, eastern part of India, was observed during the event of southwest to northeast monsoon transition. Increase in nitrate, total nitrogen, and silicate concentrations were noticed during post-transition period. Ammonia concentration was at peak during transition period as compared to pre- and post-transition periods. Hypo-saline condition (~23 psu) was observed during post-transition as the surface water salinity decreased by ~10 psu from the pre-transitional values. Turbidity, suspended particulate matter, phosphate and total phosphorous values decreased marginally, coinciding with northward to southward current reversal. A drastic decrease (eightfold) in chlorophyll-*a* concentration was observed in the coastal water during post-transition period.

Keywords Monsoon transitions · Coastal waters · Physicochemical properties · Nutrients · Bay of Bengal · East cost of India

K. K. Satpathy (✉) · A. K. Mohanty · G. Sahu · M. V. R. Prasad
Environmental and Industrial Safety Section, Indira Gandhi Centre for Atomic Research, Kalpakkam 603 102, Tamil Nadu, India
e-mail: satpathy@igcar.gov.in

A. K. Mohanty
e-mail: ajit@igcar.gov.in

G. Sahu
e-mail: gouri@igcar.gov.in

M. V. R. Prasad
e-mail: mvrp@igcar.gov.in

U. Natesan
Centre for Environmental Studies, Anna University, Chennai 600 025, India

R. Venkatesan
National Institute of Ocean Technology, Chennai 601 302, India

S. K. Sarkar
Department of Marine Science, University of Calcutta, Kolkata 700 019, India

Introduction

Seasonal monsoon reversal of wind is a unique feature of Indian Ocean that results in consequent change in the circulation pattern (Anonymous 1952; La Fond 1957; Wyrtki 1973). The wind reversal occurs during the transition period between the southwest (SW) monsoon and northeast (NE) monsoon. In general, the SW to NE monsoon transition occurs during September/October and the NE to SW transition occurs during February/March. The pole-ward current during SW monsoon changes to equatorward during the SW to NE monsoon transition, whereas, a reverse current pattern is observed during the transition period between NE and SW monsoon (Varkey et al. 1996; Vinayachandran et al. 1999; Haugen et al. 2003). Subsequent to the change in the current pattern, the alterations of coastal water quality have been reported (Somayajulu 1987; Ramaraju et al. 1992; Babu 1992; Saravanane et al. 2000). Though several authors have studied the circulation pattern in Bay of Bengal (BOB) during the transition periods, the studies have been confined to some hydrographical parameters like temperature and salinity (Ramaraju et al. 1992; Babu 1992) and rarely the plankton (Saravanane et al. 2000). Detailed investigation on the alteration of the coastal water quality of BOB in general and at Kalpakkam coast in particular during transition period is meager. Against this backdrop the present study was designed to investigate for a comprehensive account of the physico-chemical alterations of the coastal waters and its impact on the productivity of this area during the summer monsoon to winter monsoon transition. Data generated in this study were subjected to multivariate statistical methods such as cluster analysis and principle component analysis so as to elucidate the physico-chemical state of the coastal waters during pre-transition, transition, and post-transition periods.

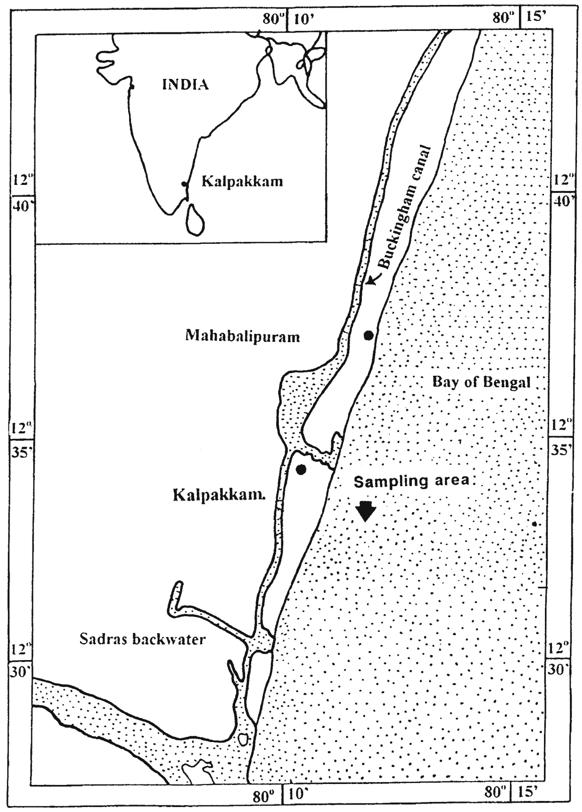

Fig. 1 Map of study area showing sampling location

Materials and methods

Study area

Kalpakkam is situated at 12°33′ N Lat. and 80°11′ E Long. along the Indian east coast (Fig. 1). According to the climatology of this area the whole year has been divided into three seasons viz: (1) post-monsoon/summer (February–May), (2) pre-monsoon or SW monsoon (June–September), and (3) NE monsoon (October–January) (Satpathy 1996). The NE monsoon is active in this area and bulk (80%) of rainfall occurs during this period. Due to the geographic location of this area, the monsoon reversal of wind and the subsequent change in the current pattern is prominent here leading to a visible alternation of the coastal milieu.

Methods

Surface seawater samples were collected daily for a period of 2 months (14th September to 13th November, 2006) covering the transition period. A fixed location at the jetty of the Madras Atomic Power Station, ~500 m inside the sea was chosen for sampling (Fig. 1). Current speed and direction was measured following the drift bottle technique. A mercury thermometer having 0.1°C resolution was used for measurement of water temperature. Winkler's titrimetric method was followed for the estimation of dissolved oxygen (DO). Salinity measurements were carried out by Knudsen's method (Grasshoff et al. 1983). Biochemical oxygen demand (BOD) of the samples was calculated after an incubation period of 5 days in BOD incubator. pH measurement was carried out by a pH meter (CyberScan PCD 5500) having a resolution of 0.01. Turbidity of the water samples was measured by turbidity meter

(CyberScan IR TB 100) having 0.01 NTU resolution. Suspended particulate matter (SPM) of the samples was measured following the method of Grasshoff et al. (1983). The dissolved micronutrients such as, nitrite, nitrate, ammonia, silicate, phosphate along with TN and TP were estimated by following standard methods (Grasshoff et al. 1983; Parsons et al. 1984), after filtering the water samples through 0.45 μ Millipore filter paper. Chlorophyll-*a* was analyzed by spectrophotometry following the method of Parsons et al. (1984). For all the spectrophotometric analyses, a double beam UV-Visible Spectrophotometer (Chemito Spectrascan UV 2600) was used. All the data obtained during the present study were categorized into five groups such as north, NE, east, southeast (SE), and south, based upon the direction of the water current during the daily observations. Statistical analyses such as correlation matrix, cluster analysis, and principal component analysis (PCA) were carried out by using XLStat Pro software.

Results and discussion

Current direction and speed

Current direction during the study showed a typical step-by-step change from north to south with transitional directions towards NE, east, and SE. Though the transitional directions were observed for a shorter period, it was prominent enough to be detected. The NE direction was observed for more than a week, whereas, the other two periods such as east and SE direction of circulation together existed for a week. The present study clearly showed that a transition (when the current was shifting from north to south) period of about 20 days. The previous study from this locality, the only one (Saravanane et al. 2000) does not mention about the lull period (northeast, east, and southeast). The highest current velocity value of 0.53 m s^{-1} was observed during the northward circulation whereas, the lowest value (0.08 m s^{-1}) was observed during the eastward circulation. The period wise average values of current velocity showed that it was maximum during northward circulation and decreased sharply during the northeast current direction after which it gradually increased to attain almost similar velocity as that of the northward circulation period (Fig. 2 (1)). During the NE and eastward circulation periods the coastal water became almost stable with negligible current velocity. Current magnitude was relatively high during pre-transition period, which could be due to relatively high intensities of wind stress prevailed during SW monsoon that gradually decreased during transition period (northeast to southeast current direction) resulting in diminution of current speed (Unnikrishnan and Bahulayan 1991). The lower intensity of current observed during northeast to east direction period might indicate the withdrawal phase of SW monsoon (Somayajulu et al. 1987) and beginning of transition before the NE monsoon sets in. An earlier report by Somayajulu et al. (1987) indicated eastward transport as a result of the waters brought by a southerly flow from the northern bay and a northerly flow from southern bay. This period of transition, before a steady state indicating clear direction of current, reported to range from 2 weeks to 1 month in the tropical region (Babu 1992). With the onset of NE monsoon, the surface water of BOB moves towards south resulting in arrival of new water mass in coastal areas (Muraleedharan 1993; Somayajulu et al. 1987; Unnikrishnan and Bahulayan 1991). Although, it is fairly logical to attribute these changes primarily to wind, the role of horizontal density differences in this water movement cannot be ignored. It is worthwhile to mention that the perennial rivers in the north region empty into the bay creating a horizontal salinity gradient, which intensifies the circulation coupled with the NE monsoonal wind resulting in a reasonably steady coastal current in the western boundary of BOB (Shetye et al. 1991, 1993).

Temperature

The surface water temperature during the present study ranged from 28.5 to 30.6°C. It gradually increased with current reversal from north to south (Fig. 2 (2)). A similar variation of temperature has been reported earlier (Saravanane et al. 2000) during SW to NE monsoon transition at this location where it was attributed to the equatorward flow of low saline and high temperature

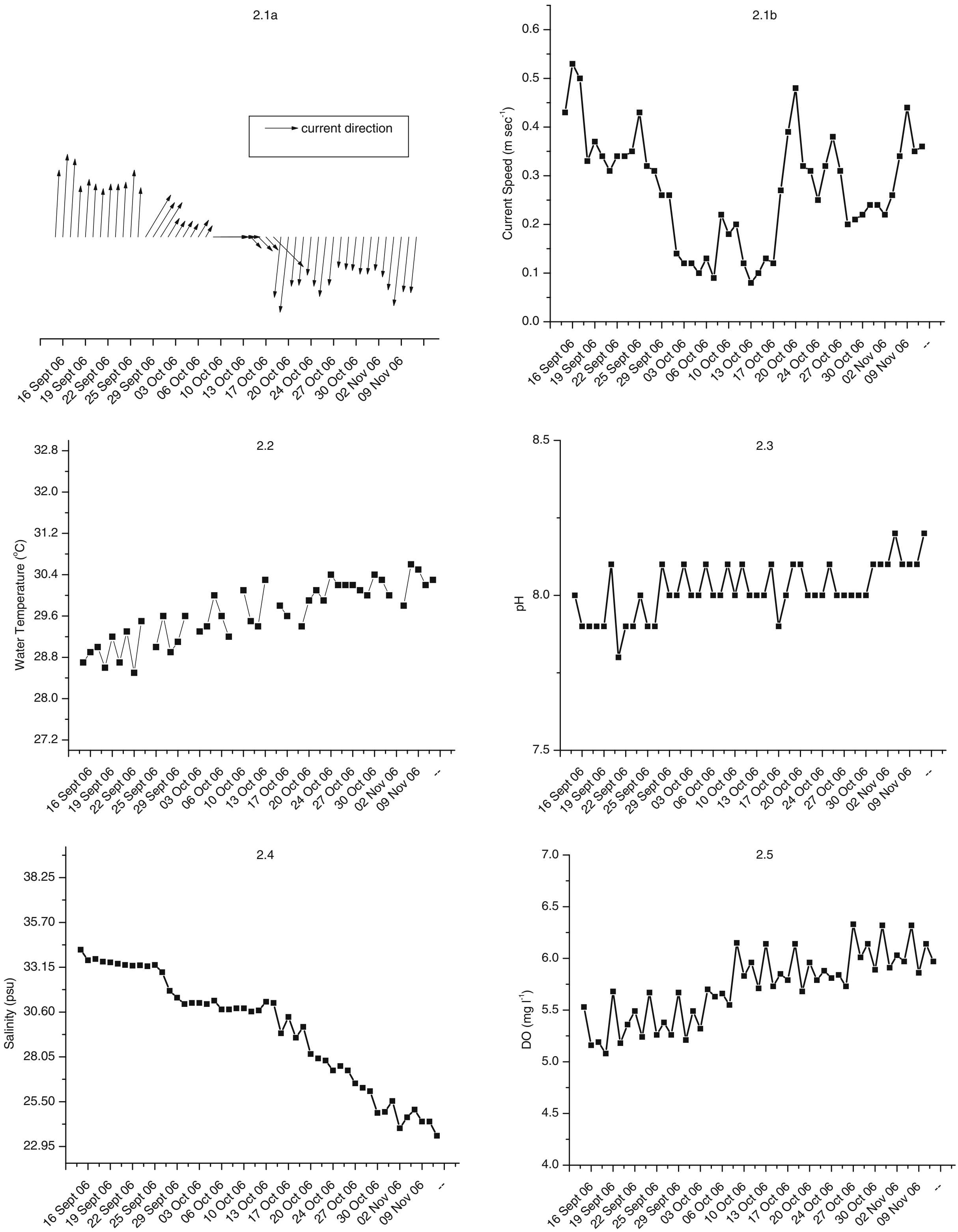

Fig. 2 (*1–8*) Variation of hydrographical parameters during the SW to NE transition in the coastal waters of Kalpakkam. (*9–16*) Variation of nutrients and chlorophyll-*a* during the SW to NE transition in the coastal waters of Kalpakkam

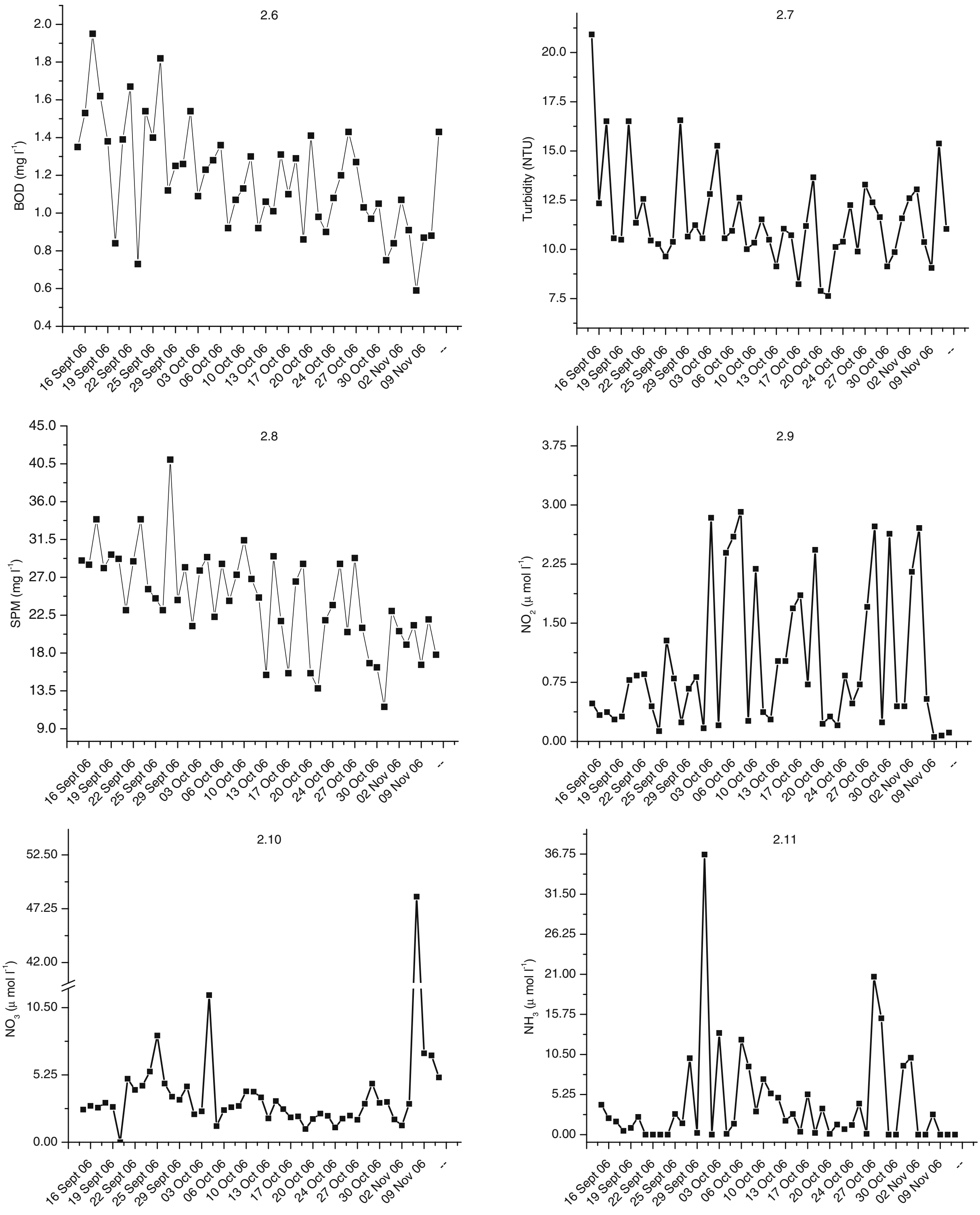

Fig. 2 (continued)

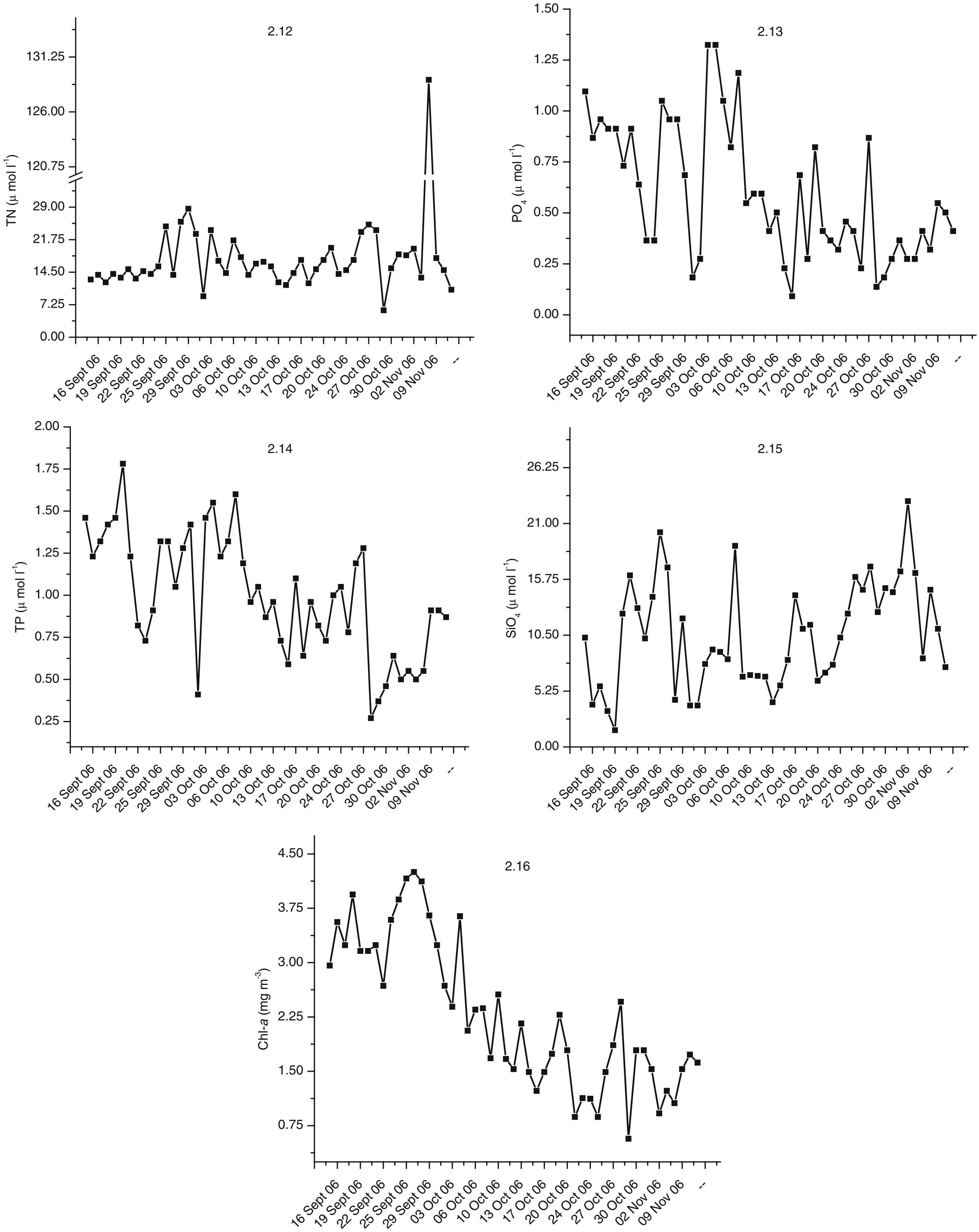

Fig. 2 (continued)

surface water mass form the northern to southern part of the BOB. Seawater temperature is well known to depend on a number of factors such as, atmospheric temperature, wind magnitude, solar radiation, cloud coverage and salinity gradient (due to freshwater discharge). In the southeast coast of India, air temperature shows a bimodal oscillation with two peaks, one during Apr./May and another during Sep./Oct. (Satpathy and Nair 1990). The sea surface temperature (SST) regime of the BOB has been described in detail by Sadhuram et al. (2004). The SST variation in the BOB region is mostly due to the march of sun. With the onset of SW monsoon (June–September), the temperature decreased, which could be due to the loss of energy from the sea surface to the atmosphere by evaporational cooling as a result of the impact of strong monsoonal winds. This is coupled with reduction in the incoming solar radiation by clouds resulting in cooling of sea surface. Moreover, upwelling, a well-known phenomenon during SW monsoon period is also responsible for relatively low temperature. With the change in current from north to south during post-SW monsoon or post-transition period, the depth of mixed layer increases due to the massive mixing of riverine freshwater (559×10^9 m^3) from the rivers of northern BOB resulting in low saline surface water exposed to increased solar radiation as the cloud coverage reduced during October. This explanation is strengthened by the fact that the heat potential in the BOB during October (>16 k cal/cm^2) is relatively high as compared to SW monsoon period (10–18 k cal/cm^2; Sadhuram et al. 2004). Moreover, temperature conditions in coastal and estuarine environments fluctuate depending upon their bathymetry, insolation, local atmospheric variation, and land drainage (Alvarez-Borrego and Alvarez-Borrego 1982).

pH

pH values did not show significant variation during the present study which ranged from 7.8 to 8.2. The average values for different periods such as north, NE, east, SE, and south showed that (Fig. 2 (3)) pH values increased from north to NE observations after which it remained almost stable except for a marginal decrease during the SE current direction. The observed insignificant variation in pH observed could be attributed to the negligible terrestrial runoff and precipitation during this period coupled with the extensive buffering capacity of the seawater that causes the change of pH within a very narrow limit (Riley and Chester 1971).

Salinity

Decrease in the values of salinity was noticed during the north to south current reversal. The values ranged from 23.56 to 34.15 psu, lowest being observed during southward current and highest being observed during northward current pattern (Fig. 2 (4)). The reduction of salinity during the late transition period could be due to the inflow of low saline water from the northern BOB, wherein some of the major perennial rivers debouch huge quantity of freshwater. Salinity showed negative correlations of with DO ($p \geq 0.001$) and silicate ($p \geq 0.005$). Since, solubility of DO decreases with increase in salinity and freshwater is considered as the main source of silicate in the coastal environment, the above negative correlation could be due to the intrusion of water mass with low saline and high silicate content to this coastal water. Since, phosphate is considered to be of marine origin in non-polluted environments, the strong positive correlation ($p \geq 0.001$) of salinity with phosphate and TP showed that, the coastal water salinity and phosphate concentration decreased with the intrusion of low saline water mass. Similar change in salinity concentrations during SW to NE monsoon transition has been reported by others (Saravanane et al. 2000).

Dissolved oxygen

The dissolved oxygen contents varied between 5.08 and 6.33 mg l^{-1}. An increase in DO contents was observed from north to east current change and then it remained almost stable for the rest of the study period (Fig. 2 (5)). The variation of DO in coastal waters is a function of physico-chemical properties of water, which alter its solubility (Aston 1980) and also as a result of

Table 1 Correlation matrix (Pearson) of the various physico-chemical parameters of the coastal waters of Kalpakkam during the southwest to northeast monsoon transition

Variables	Temp.	pH	Salinity	DO	BOD	Turbidity	SPM	Nitrite	Nitrate	Ammonia	TN	Silicate	Phosphate	TP	Chl-*a*
Temp.	1														
pH	0.400*	1													
Salinity	−0.776*	−0.575*	1												
DO	0.753*	0.465*	−0.752*	1											
BOD	−0.457*	−0.366*	0.509*	−0.448*	1										
Turbidity	−0.480*	0.092	0.212	−0.262***	0.075	1									
SPM	−0.617*	−0.225	0.604*	−0.543*	0.249***	0.563*	1								
Nitrite	0.084	0.001	−0.112	0.039	−0.158	−0.001	−0.051	1							
Nitrate	0.255***	−0.076	−0.184	0.221	−0.255***	−0.055	−0.055	−0.153	1						
Ammonia	0.042	0.024	−0.007	−0.067	−0.094	0.115	0.225	0.279***	−0.057	1					
TN	0.241***	−0.021	−0.217	0.228	−0.311**	−0.073	−0.034	0.006	0.922*	0.115	1				
Silicate	0.110	−0.013	−0.354**	0.192	−0.176	0.017	−0.312**	0.381*	−0.036	−0.066	0.008	1			
Phosphate	−0.538*	−0.328**	0.551*	−0.494*	0.309**	0.423*	0.437*	0.165	−0.052	0.028	−0.069	−0.044	1		
TP	−0.556*	−0.318**	0.615*	−0.555*	0.329**	0.321**	0.450*	−0.016	−0.139	0.193	−0.108	−0.166	0.784*	1	
Chl-*a*	−0.634*	−0.475*	0.749*	−0.737*	0.493*	0.278***	0.549*	−0.118	−0.061	0.097	−0.114	−0.121	0.573*	0.556*	1

$^{*}p \geq 0.001$; $^{**}p \geq 0.005$; $^{***}p \geq 0.01$

imbalance between the process of photosynthesis, degradation of organic matter, and reaeration (Granier et al. 2000). The increase in DO with decrease in salinity of the coastal waters showed the classical relationship between these two parameters as mentioned earlier (Table 1). Though a positive correlation ($p \geq 0.001$) was observed between DO and temperature, the lower salinity could be the reason behind the higher oxygen content of the coastal water with marginally higher temperature. The negative correlation ($p \geq 0.001$) of DO with chlorophyll showed that the photosynthetic release of DO during this period was negligible. This could be due to the hindrance of reproduction and survivability in phytoplankton in a relatively low saline medium.

Biochemical oxygen demand

A gradual decrease in the BOD values was observed during the north to southward current reversal (Fig. 2 (6)). The values ranged from 0.59 to 1.59 mg l^{-1}, highest and lowest being observed during northward and southward circulation, respectively. Marine microorganisms including phytoplankton, responsible for the BOD solely depend upon the salinity factor for their growth and reproduction and might have been eliminated due to lower salinity during the transition and post-transition period, resulting in gradual decrease in BOD contents. Moreover, the lower BOD contents could be due to lower pollution load and low organic matter in the coastal water during the transition period. The strong positive correlation ($p \geq 0.001$) of BOD with chlorophyll-*a* showed that phytoplankters significantly contributed to the BOD of the coastal water. Hence, the BOD content of the coastal water decreased with gradual decrease in the chlorophyll-*a* contents from north to south current reversal. A weak positive correlation ($p \geq 0.01$) of BOD with SPM also supported the above observation as the microorganisms including plankton significantly contribute towards the SPM content in the coastal waters.

Turbidity

The values of turbidity ranged from 7.63 to 20.92 NTU during the present study, highest being observed during northward current direction and lowest during the southward current direction. Turbidity or water transparency is an important water quality parameter, which decides the depth of euphotic zone and thus indirectly acts as one of the key factors for productivity potential of coastal waters. A gradual decrease in turbidity value was noticed during the change of current direction from north to east after which it remained almost stable in the rest of the study period (Fig. 2 (7)). Turbidity showed a strong positive correlation ($p \geq 0.001$) with SPM and a weak positive correlation ($p \geq 0.01$) with chlorophyll-*a* confirming that the SPM, including the phytoplankton, mainly contributed to the turbidity of the coastal water. The turbidity gradually decreased with the decrease in the SPM and phytoplankton biomass with reversal of current.

Suspended particulate matter

The SPM values observed, followed almost similar pattern of variation to that of the turbidity (Fig. 2 (8)). Its values ranged between 11.60 and 41.00 mg l^{-1}. Phytoplankton population and turbidity, which significantly contribute to the SPM values in marine waters, decreased from northward to southward circulation which could be the reason for the gradual decrease in SPM content. This is further supported by the strong positive correlations ($p \geq 0.001$) of SPM with chlorophyll-*a* and turbidity.

Nitrite

Concentration of nitrite in the coastal waters did not show any significant variation during the present study (Fig. 2 (9)). It ranged from 0.06 to 2.91 μmol l^{-1}. The highest and lowest values were obtained during pre- and post-transition periods, respectively. Nitrite, the intermediate oxidation state between ammonia and nitrate, can appear as a transient species by the oxidation of ammonia or by the reduction of nitrate. Thus, being the most unstable form of dissolved inorganic nitrogen species present in seawater, nitrite level showed wide fluctuations during the present investigation. According to Santschi et al. (1990) and Chandran and Ramamurty (1984) nitrite is often released into the water as an extracellular product of the planktonic organisms. Thus, nitrite distribution depicts irregular picture and wide variations in coastal milieu.

Nitrate

Nitrate values ranged from 1.035 to 48.43 μmol l^{-1}. The lowest value was observed during the transition period (prior to southward current direction), whereas, highest value was observed during the post-transition period. Its concentration gradually decreased from the pre-transition period with clockwise change in current direction from north to SE, with a visible increase in the post-transition period when the current direction was towards south (Fig. 2 (10)). Out of the nine oxidation states (−3 to +5) of nitrogen, nitrate is thermodynamically the most stable form of combined inorganic nitrogen in well-oxygenated waters. Variations in nitrate and its reduced inorganic compounds are predominantly the results of biologically activated reactions. Quick assimilation by phytoplankton and enhancement by surface runoff results in large-scale spatio-temporal variation of nitrate in the coastal milieu (Qasim 1977; De Souza 1983; Zepp 1997; Choudhary and Panigrahy 1991). The visible increase in nitrate concentration during the post-transition period could be due to the intrusion of low saline high nitrate content water mass from northern BOB. Furthermore, the biological consumption, particularly the phytoplankton uptake, during the post-transition period could be low leading to increased nitrate content in the medium. Nitrate showed a strong positive correlation ($p \geq 0.001$) with TN, which shows that it contributed significantly to the TN concentration.

Ammonia

Ammonia values were bellow detection limit on many occasions particularly during north, NE, and southward current direction. However, during east and SE current flow its values never reduced BDL (below detection limit). It ranged from BDL to 30.70 μmol l^{-1}. Average values for individual periods of current direction showed a visible increase in ammonia content during north-east current direction after which it gradually decreased and remained almost stable in the later part of the transition period (Fig. 2 (11)). The above behavior of ammonia could be ascribed to the different dynamic conditions of the sea. During early transition when the dynamics of the sea was at highest the ammonia produced by the organisms was removed or utilized quickly whereas, its removal from the medium decreased with the reduced dynamism of the coastal environment in later periods. It did not show any significant correlation with any parameter except a weak positive correlation ($p \geq 0.01$) with nitrite, which could be due to the fact that oxidation of ammonia results in the synthesis of nitrite. Ammonia, the chief excretory product of the marine invertebrates, is also well known as a nutrient, which is preferred over nitrate by the phytoplankton community in certain environmental conditions. Thus, excretory release and utilization by phytoplankton significantly affects the concentration of ammonia (Olson 1980; Gilbert et al. 1982) in the marine environment. Relatively high standard deviation observed for ammonia indicated wide fluctuation. This irregular trend of ammonia could also be due to its oxidation to other forms or reduction of nitrate to lower forms in coastal waters as reported by Sankaranrayanan and Qasim (1969).

Total nitrogen

TN values ranged from 6.02 to 129.0 μmol l^{-1} and both the highest and the lowest values were observed during the post-transition period. A marginal increase in TN concentration was noticed after the current reversal as compared to pre-transition as well as transition period (Fig. 2 (12)). Similar to that of nitrate, the fluctuations were relatively high during the post-transition period. TN did not show any significant correlation with any parameter except a strong positive correlation ($p \geq 0.001$) with nitrate, which showed that nitrate contributed to the TN concentration significantly.

Phosphate and total phosphorous

Concentration of phosphate and TP exhibited almost similar pattern of variation during this study. The values ranged from 0.09 μmol l^{-1} during late transition (southeast current) to 1.32 μmol l^{-1} during early transition (northeast current) for phosphate. Similarly, highest TP value (1.78 μmol l^{-1}) was observed during pre-transition (northward current) and lowest (0.27 μmol l^{-1}) during post-transition (southward current) period. Both, phosphate and TP contents, remained stable during north and northeast current directions; however, gradually decreased from NE to SE and remained stable during the later part of transition (Fig. 2 (13 and 14)). A strong positive correlation ($p \geq 0.001$) between phosphate and TP showed that inorganic phosphate significantly contributed to the TP concentration. Both phosphate and TP showed strong positive correlation ($p \geq 0.001$) with salinity. This showed that lower concentration of phosphate during the later part of transition is due to dilution of the coastal water with hypo-saline water mass with lower phosphate content. Moreover, phosphate concentration in coastal waters depends upon its concentration in the freshwater that mixed with the seawater within the land–sea interaction zone, phytoplankton uptake, addition through localized upwelling and replenishment as a result of microbial decomposition of organic matter. A strong positive correlation ($p \geq 0.001$) of phosphate and TP with chlorophyll-*a* showed that phosphorous, which could be a limiting factor for phytoplankton growth (Cole and Sanford 1989), is dominant over nitrogen at this location during the study period.

Silicate

Silicate values ranged from 1.58 to 23.10 μmol l^{-1}. A gradual decrease in silicate concentration during northward to eastward change in current was noticed after which it again increased up to the post-transition period (Fig. 2 (15)). Silicate showed a moderately strong negative correlation ($p \geq 0.005$) with salinity. Since freshwater is the main source of silicate (Lal 1978), the above negative correlation of silicate with salinity described the drift of silicate rich hypo-saline water from northern BOB, as the other possibilities like precipitation and land drainage to the coastal water was not there during this period. Apart from the physical mixing of seawater with freshwater (Purushothaman and Venugopalan 1972), factors like adsorption of reactive silicate into suspended sedimentary particles (Lal 1978), chemical interaction with clay minerals (Aston 1980; Gouda and Panigrahy 1992), co-precipitation with humic compounds and iron (Stephns and Oppenheime 1972), and biological removal by phytoplankton, especially by diatoms and silicoflagellates (Rao 1969; Aston 1980; Liss and Spencer 1970) can significantly affect the spatio-temporal variation of silicate in coastal waters.

Chlorophyll-*a*

The chlorophyll-*a* values gradually decreased from north to southward as the current direction

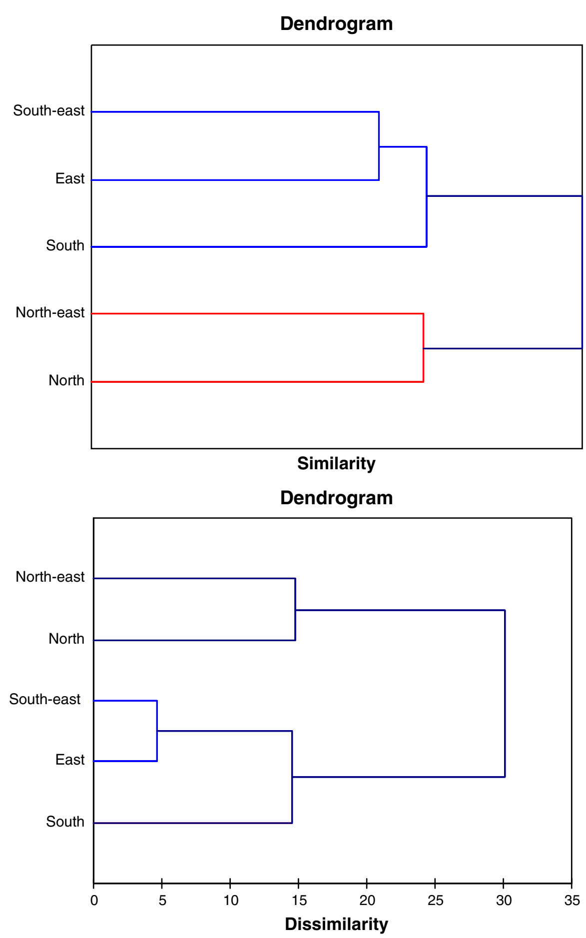

Fig. 3 (*1* and *2*) Dendrogram showing similarity and dissimilarity clusters of different periods of current directions

changed and remained almost stable during the later half of the transition period (Fig. 2 (16)). It ranged from 0.57 mg m^{-3} during the southward circulation to 4.25 mg m^{-3} during the northward current direction. Strong positive correlation ($p \geq 0.001$) of chlorophyll-*a* with salinity showed that ~10 psu decrease in salinity from pre- to post-transition period significantly affected the phytoplankton growth and reproduction resulting in the lower phytoplankton growth. The Primary productivity potential of the marine environments depends upon the phytoplankters, which alone contributes ~90% of the total marine primary production. Thus, chlorophyll-*a*, which constitutes the chief photosynthetic pigment of phytoplankters, is an index that would provide the primary production potential upon which the biodiversity, biomass, and carrying capacity of that system depends. The increased temperature and pH also could have hampered the phytoplankton productivity and the same is reflected with negative correlation of these two parameters with chlorophyll-*a*. As described earlier, phosphate and TP were found to be the limiting factor for phytoplankton growth during this study.

Cluster analysis

Data grouped according to the surface water current direction were analyzed for both similarity and dissimilarity clusters. The dendrogram for similarity showed two clusters (Fig. 3 (1)). The groups north and northeast formed the first cluster, whereas, east, southeast, and south formed the other cluster. This showed that during the period of north and northeast current direction the coastal water quality was almost similar. Similarly, the other cluster formed showed that the period of east, southeast, and south current direction behaved as a single time period as far as the water quality is concerned. In the dissimilarity cluster analysis four clusters were formed (Fig. 3 (1)). Groups such as north, northeast, and south individually formed one cluster each, whereas, east and southeast together formed one cluster. A similar pattern of behavior in the coastal water body, as was noticed from the similarity cluster, was seen in dissimilarity clusters also. The dissimilarity between the individual periods of transition was less compared to the dissimilarity between the two groups they formed, i.e., one by northeast and

Table 2 Eigenvalues and factor loadings of principal component analysis

	F1	F2	F3	F4	F5	F6
Eigenvalue	5.698	2.000	1.753	1.357	1.186	0.841
Variability (%)	35.615	12.500	10.955	8.484	7.411	5.256
Cumulative %	35.615	48.116	59.071	67.555	74.966	80.222
Factor loadings						
Current speed	0.334	0.241	−0.439	0.129	0.478	0.486
Temperature	−0.865	0.050	0.015	−0.054	−0.178	0.018
pH	−0.534	−0.195	0.138	0.628	0.062	−0.191
Salinity	0.888	0.017	−0.086	−0.127	−0.244	−0.149
DO	−0.849	0.028	0.029	0.097	0.057	−0.103
BOD	0.597	−0.183	−0.358	−0.180	−0.037	0.114
Turbidity	0.448	0.069	0.344	0.566	0.460	−0.036
SPM	0.710	0.176	0.215	0.383	−0.092	0.030
Nitrite	−0.106	−0.265	0.755	−0.361	0.004	0.009
Nitrate	−0.245	0.936	0.022	−0.115	0.038	−0.103
Ammonia	0.071	0.048	0.587	0.179	−0.427	0.608
TN	−0.270	0.906	0.192	−0.110	−0.016	0.002
Silicate	−0.256	−0.189	0.347	−0.447	0.644	0.149
Phosphate	0.718	0.092	0.334	−0.102	0.184	−0.312
TP	0.752	0.068	0.234	−0.007	−0.021	−0.140
Chl-*a*	0.829	0.117	0.012	−0.148	−0.060	0.029

north and the other by east, southeast, and south (Fig. 3 (1)). The above analysis showed that there is a distinct change in the water quality of the coastal waters during the southwest to northeast monsoon transition period at this part of the east coast of India.

Principal component analysis

PCA of the water quality data during the present study developed six principal components (PC) as can be determined from the eigenvalues (Table 2). It explained 80.22% of the total data variability in this coastal water within this short period of study. PC-1 accounted for 35.615% of the total variance with negative factor loadings of temperature, pH, DO, nitrite, nitrate, TN, and silicate (Table 2). In PC-2 positive loadings of almost all the parameters can be seen except pH, BOD, nitrite, and silicate that contributed 12.50% of the total variability. Whereas, in PC-3 the negative loadings of parameters further decreased and restricted to the three parameters such as current speed, salinity, and BOD in PC-3 which accounted for 10.955% of the total variability. PC-4, 5, and 6 showed increased negative loading of various parameters and accounted for 8.484%, 7.411%, and 5.256% of the total variability.

Conclusion

Biannual current reversal in BOB is one of the striking features of this large marine ecosystem (LME-34) during which a substantial change in its biogeochemistry takes place in regional scale. In the present study, temperature, DO, and silicate increased during the post-transition period compared to the pre-transition period. In contrast, a significant decrease in salinity, turbidity and SPM, phosphate, and chlorophyll-*a* was observed from pre- to post-transition period. Thus, pre-transition, transition, and post-transition periods were characterized by different physicochemical and biological properties, typical of each period coinciding with the change in current direction from north to south. The above observation was also strengthened by the cluster analysis results.

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