

04.12.2017

Perennial occurrence of heterotrophic, indicator and pathogenic bacteria in the coastal Bay of Bengal (off Visakhapatnam) - Impact of physical and atmospheric processes

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Abstract

In order to examine the health of the coastal waters off Visakhapatnam in terms of prevalence and abundance of heterotrophic (H), indicator and pathogenic (P) bacterial counts (BC) and influence of physical processes on them, time-series observations were conducted during January (winter), March (spring), July (summer) and October (post-monsoon). We noticed the impact of physical forces on substantial variations in abundance and distribution of the HBC, total coliforms, *Enterococcus faecalis* and *Pseudomonas aeruginosa* in the study region. Based on our results *Escherichia coli* and other PBC were not much influenced by the physical conditions. It has been noticed that the perennial existence of the high abundance of IBC and PBC above the standard limits during the entire study period leading to an alarming situation in the coastal waters off Visakhapatnam.

Key words: Upwelling; Hud hud cyclone; pathogenic bacteria; heterotrophic bacteria; pollution; coastal Bay of Bengal.

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1. Introduction

Conventionally, indicator bacteria have been used to advocate the prevalence of pathogens (Berg, 1978). Indicator bacteria are two groups which reveal the efficiency of a process like to know the chlorine disinfection (total coliforms (TC)) and another group shows the occurrence of faecal contamination, such as the bacterial groups *Escherichia coli* (EC) or *Enterococcus faecalis* (EF) which surmise that pathogens may be present (Nicholas et al., 2001). Coliforms endure in a marine environment for multiple weeks (Patti et al., 1987, Piccolomini et al., 1987) and are the prevailing bacteria in the land driven discharges and their existence in the marine environment is considered an indicator of water pollution. There are several adverse conditions and agents which reduce the viability of these bacteria in the marine environment (Robin et al., 2012, Rozen and Belkin, 2001). Contamination of coastal waters with human pathogens is documented (DebRoy et al., 2012, Nagvenkar and Ramaiah, 2009, Patra et al., 2009, Prasad et al., 2015, Robin et al., 2012, Rodrigues

et al., 2011). There are several dreadful diseases like cholera, diarrhoea, dysentery and typhoid fever were caused due to different water born pathogenic microbes. Waterborne outbreaks of pathogenic bacteria from contaminated water are serious threats to public health.

The Bay of Bengal, northeastern part of Indian Ocean, is one of the largest bay in the world covers an area of 2,172,000 km² and receives huge anthropogenic inputs from large rivers, such as the Ganges, Brahmaputra, Irrawaddy, Mahanadi, Godavari, Krishna etc. (Varkey et al., 1996). As a result of the freshwater discharge, the upper water column stratifies resulting in weak vertical mixing (Prasanna Kumar et al., 2002). The Bay of Bengal coast is shared by several under-developed and developing countries which discharge several pollutants. The seasonal reversing in East Indian coastal currents (EICC) distributes these pollutants along the east coast of India (Varkey et al., 1996). Recently Prasad et al. (2015) reported spatial distribution of heterotrophic, indicator and pathogenic bacteria along the east coast of India due to discharge of freshwater from various rivers, which receive variable magnitude of pollutants. They noticed that higher viable bacterial counts in the coastal waters, off Visakhapatnam, than regions which are influenced by river discharge, due to the discharge of and attributed a significant amount of domestic and industrial sewage. These microbes coming from domestic and industrial activities finally can cause illness to human using recreational activities in the coastal waters or by taking fouled marine foodstuff. Organic matter is a substratum to the bacteria for their growth and several physical processes in the coastal waters supports their production. For instance, coastal upwelling during March to September, vertical mixing due to cyclones during October to December and Ekman pumping during January to March bring nutrient-rich subsurface waters to the surface that promotes phytoplankton production (Maneesha et al., 2011, Sarma et al., 2013). The enhanced organic matter production through *in-situ* processes may support heterotrophic bacterial abundance in the coastal waters. In order to examine health of the coastal waters, in terms of heterotrophic, indicator and pathogenic bacteria, the time-series observation were conducted at 6 stations in the coastal Bay of Bengal, off Visakhapatnam, during four different months (January, March, July and October) corresponding to four different seasons (winter, spring, summer and post-monsoon) to examine distribution of heterotrophic, indicator and pathogenic bacteria. The questions addressed in this study are: 1) What is the abundance and distribution of heterotrophic, indicator and pathogenic bacteria in the coastal Bay of Bengal? 2) What is the role of physical and atmospheric processes on the spatial and temporal variations of these bacteria in the

water column? and 3) Assessment of quality of coastal waters of Bay of Bengal, off Visakhapatnam, with reference to bacterial population.

2. Materials and methods

2.1. Study site

The north-eastern Indian Ocean (Bay of Bengal) is a distinctive tropical ecosystem which receives enormous amount of freshwater discharge ($1.6 \times 10^{12} \text{ m}^3 \text{ year}^{-1}$) through various rivers, such as Ganges, Brahmaputra, Irrawaddy-Salween, Godavari, Krishna, Mahanadi etc. resulting in reduced salinity in the upper ocean (Varkey et al., 1996; Prasanna Kumar et al., 2002). The coastal circulation reverses its direction from equatorward during summer and poleward during post-monsoon and winter (Varkey et al., 1996). Cyclones/depression are formed every year during summer and post-monsoon periods resulting in high productivity (Maneesha et al., 2011). Based on the occurrence of unique physical processes, the study region is divided into three different periods, viz., winter (December-February) spring (March-May) and summer (June-September) and fall monsoon (October-November) periods. The continental shelf in the study region is quite steep common to the bay (except in Gangetic basin) compared to the Arabian Sea, and the 100 m contour occurs at ~17 nautical miles from the coast (Fig. 1).

2.2. Sample collection and analysis

The sampling was performed in the coastal and off-shore regions of the Bay of Bengal at six preset stations (Fig. 1) at standard depths during four different months, January, March, July and October 2014. Vertical profiles of pressure, temperature and salinity were measured using a portable conductivity, temperature and depth (CTD) profiler (SBE 19 plus; Sea Bird Electronics, USA). Water samples were collected from standard depths using a 10 L Niskin bottle. Bubble-free water samples were first taken for dissolved oxygen (DO) measurements following the Winkler titration method of Carritt and Carpenter (1966). The analytical precision, expressed as standard deviation, was 0.07 % for oxygen. The concentrations of nutrients were measured following standard spectrophotometric procedures using an autoanalyzer (Technicon; Traacs, Australia) (Grasshoff et al., 1983). The detection limits for nitrate, ammonium and phosphate were ± 0.05 , ± 0.05 and $\pm 0.02 \mu\text{M}$ respectively. A 2-L water sample was filtered through a GF/F filter ($0.5 \mu\text{m}$ pore size; Whatman). Chl-*a* on the filter was first extracted with N, N-dimethylformamide (DMF), at 4°C in

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the dark for 12 h and then spectrofluorometrically analysed (Varian Eclipse fluorescence photometer) following Suzuki and Ishimaru (1990). The analytical precision for Chl-*a* analysis was $\pm 4\%$.

About 100 ml of sample was taken into a pre-sterilized bottle for bacterial analysis. All samples were collected with precautions required for microbiological analysis and analysed after transporting to the laboratory. The bacteriological examinations were done following Ramaiah et al. (2004) and Prasad et al. (2015) for the enumeration of heterotrophic, indicator and few pathogenic bacteria. The different selective media's were used for the specific bacterial groups. Heterotrophic bacterial counts were determined on R2A agar, enumeration of coliforms on McConkey agar, *Aeromonas* on *Aeromonas* Isolation agar, *Enterococcus faecalis* on Rapid HiEnterococci (RHE) agar, *Escherichia coli* O157:H7 on HiCrome EC O157:H7 agar, *Pseudomonas* spp. on Cetrimide agar, *Salmonella* spp. and *Shigella* spp. on Xylose-Lysine-Deoxycholate (XLD) agar. *Vibrio* spp. on Thiosulphate citrate bile salts sucrose (TCBS) agar, The specific colonies (unique to the organism of interest) on the respective agar media (HIMEIDA) were quantified and the results were expressed in colony forming units (cfu ml⁻¹) according to Nagvenkar and Ramaiah (2009).

3. Results and discussion

3.1. Physicochemical properties

The water column temperatures were relatively lower during winter followed by summer, spring and post-monsoon (Fig. 2a-d). The water column was thermally stratified during spring, summer and post-monsoon period and it was weakly stratified during winter (Fig. 2a-d). The occurrence of coastal upwelling can be noticed during spring and summer as evidenced from the up sloping of isotherms from the depth of 80 to 100 m to the surface (Fig. 2b and c). Salinity showed significant seasonal variability with relatively fresh waters during post-monsoon followed by winter, spring and summer (Fig. 2e-h). The strong salinity stratification was observed during winter and post-monsoon period (Fig. 2e and h). Relatively higher phytoplankton biomass (as Chlorophyll-*a* (Chl-*a*)) was observed close to the coast (2.4 km) compared to offshore during the entire study period (Fig. 2i-l). Higher water column integrated Chl-*a* was observed during summer followed by spring due to the occurrence of coastal upwelling (Fig. 2j and k) than post-monsoon (Fig. 2l)

associated with low salinity (Fig. 2h). The highest total suspended matter (TSM) was observed during post-monsoon followed by summer (Fig. 3h and f). The lower Chl-*a* observed during post-monsoon is consistent with, the higher TSM. Dissolved oxygen (DO) concentrations vary from 55 μM to 308 μM (Fig. 3i and l). The higher DO observed during summer associated with high Chl-*a*. Ammonium, nitrate and phosphate concentrations in the water column varied from 0.03 to 4.6 μM , 0.2 to 12.9 μM and 0. to 5.6 μM respectively (Fig. 4a-l). Relatively higher ammonium and phosphate were observed during post-monsoon (Fig. 4d and l) while higher nitrate concentrations were found during spring and summer (Fig. 4f and g) suggesting that upwelling brings a significant amount of nitrate to the surface and it is consistent with Chl-*a*.

3.2. Influence of upwelling on heterotrophic, indicator and pathogenic bacterial abundance and distribution in the coastal Bay of Bengal

The coastal Bay of Bengal receives nutrients through coastal upwelling during spring and summer (March-August) leading to high phytoplankton biomass (Fig. 2j and k), and it is consistent with earlier observations (Gomes et al., 2000, Sarma et al., 2013). Upwelling phenomena start during March and gradually intensify during May to July. HB was not much abundant (4.87×10^3) during spring (Fig. 5j) compared to intense upwelling period (summer) (Fig. 5k). High abundance of HB was noticed in the upper 50 m of water column throughout the study period with higher abundance during summer (2×10^2 to 5.5×10^5 CFU/ml; Fig. 5k) due to the continuous supply of nutrients from upwelling (Fig. 2b and c) resulting in formation of organic matter through biological processes. Such high abundance in HB was consistent with high phytoplankton biomass and dissolved oxygen concentrations in the study region (Fig. 3k). Enhanced phytoplankton biomass was observed during summer associating with high concentrations of nutrients leading to the formation of fresh and labile organic matter through primary production. This fresh organic matter enhanced high abundance of HB in the study region. HB can respond quickly to the pulsed production cycles like in the upwelling (McManus and Peterson, 1988) and decomposes a major portion of dissolved organic matter generated by phytoplankton (Troncoso et al., 2003). The occurrence of higher bacterial productivity and bacterial growth rates were noticed in the upwelling compared to non-upwelling periods (Cuevas

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et al., 2004, Sorokin and Kogelschatz, 1979, Sorokin, 1981, Hanson et al., 1986, Bak and Nieuwland, 1993, Tenore et al., 1995).

The presence of TC throughout the water column during spring (Fig. 6b) indicates continuous discharge from the Visakhapatnam City. The slightly high abundance of TC was also observed in the off-shore that may be due to fishing activity and shipping traffic. The high TC during summer might be due to the availability of *in situ* organic matter generated as a result of upwelling (Fig. 6c). Although EC was part of faecal coliforms, their abundance was observed only in very few sampling points during spring (Fig. 6f) and not observed during summer (Fig. 6g). No EF counts were observed during spring (Fig. 6j), but they were higher during summer (Fig. 6k). It seems IB was not much influenced by the upwelling process during spring compared to summer.

AH counts were observed only at one station that (V3 0, 10 and 20 m) during spring (Fig. 7b) that may be due to fisherman activities and it was absent during summer (Fig. 7c). EC O157:H7 counts were observed in most of the sampling points in V1 to V3 stations and at three off-shore sampling points in V6 station during spring (Fig. 7f) and again it was absent during summer (Fig. 7g). Low abundance of EA was observed in few sampling points during spring (Fig. 7j) whereas their abundance was noticed in the upper 50 m during summer (Fig. 7k). The scattered occurrence of KP was observed during spring (Fig. 8b) and summer (Fig. 8c). SaT and Sh sp., counts were more and were mainly concentrated in the off-shore stations during spring (Fig. 8f and j), but they were absent during summer (Fig. 8g and k). PA counts were low and uniform throughout the water column during spring (Fig. 9b), but their abundance increased during summer (Fig. 9c) (1×10^3 to 1×10^5 CFU/ml) that could be due to the high availability of organic matter caused by upwelling. VC and VV counts were observed during spring (Fig. 9f) but not during summer (Fig. 9g). *Vibrio fluvialis* (VF) and VP counts were not observed in the study region (Fig. 9j and k). It shows pathogenic bacterial counts were not much affected by the influence of upwelling due to their sporadic release from those faeces which are released by infected individuals and their number is lower compared to an indicator and heterotrophic bacteria.

3.3. Influence of cyclone 'Hud hud' on heterotrophic, indicator and pathogenic bacterial abundance and distribution in the coastal Bay of Bengal

Intense winds associated with cyclones churn the upper ocean leading to the input of nutrients to mixed layer and enhanced primary production (Goldman, 1988, Taylor, 1989). Enhancement in phytoplankton abundance and productivity are generally observed during several cyclones shortly after they crossed the land (Furnas, 1989, Delesalle et al., 1993, Nayak et al., 2001, Madhu et al., 2002, Maneesha et al., 2011, Piontkovski and Al-Hashmi, 2014, Mangesh et al., 2016). Cyclones also bring the significant amount of precipitation resulting in land-drainage to the coastal waters. On 12th October 2014, Very Severe Cyclonic Storm 'Hud hud' hit the east coast of India at Visakhapatnam and it was the strongest tropical cyclone of 2014 within the North Indian Ocean, as well as the most destructive tropical cyclone that ever hit the major coastal city in India, particularly the Visakhapatnam coast. The cyclone 'Hud hud' originated from a low-pressure system that formed under the influence of an upper-air cyclonic circulation over the Andaman Sea, intensified into a cyclonic storm and as a Severe Cyclonic Storm. Shortly before the landfall near Visakhapatnam coast, 'Hud hud' reached its peak strength with wind speeds of 217 km/h and a minimum central pressure of 960 hPa. The 'Hud hud' caused extensive damage to the city of Visakhapatnam and the neighbouring districts of Vizianagaram and Srikakulam of Andhra Pradesh, India. Cyclone Hud hud significantly modified total viable bacterial counts in the coastal Visakhapatnam due to land-drainage. HB abundance was low (ranging from 5.6×10^2 to 1.6×10^4 CFU/ml (Fig. 5l) compared to summer (intense upwelling) after very severe cyclone Hud hud hit the coast. The occurrence of low saline water was observed in the upper 10 m of water column due to torrential rain followed by cyclone Hud hud leading to the low surface salinity of 18.4 to 22.5 psu with strong salinity stratification (Fig. 2h). During this time Chl-*a* concentration is less and mostly confined to coast and ranging up to 0.6 to 2.1 mg/m³ but rest of the column is between 0.1 to 0.5 mg/m³ (Fig. 2l) due to enhanced TSM from land drainage that decreases the light penetration to deep waters. Apart from this unusual conditions, HB abundance is more during this period (Fig. 5l) compared to the winter and spring (Fig. 5i and j). Such high abundance of HB is associated with high temperature, ammonium and phosphate concentrations in the water column and external source of organic matter.

Despite land drainage, a very low abundance of TC, EC and EF counts were observed during post-monsoon (Fig. 6d, h and l). It is possible that the land and the associated indicator bacteria might have been settled to the bottom in association with high total suspended matter (Fig. 3d and h). This study suggests that indicator bacterial counts were negatively influenced by the cyclone Hud hud.

AH counts were observed in the study region (Fig. 7d) due to land discharges. EC O157:H7 (Fig. 7h), KP and SaT were not observed abundantly (Fig. 8d and h). EA, PA, VC, VF, VV and VP were not observed in the entire study region during cyclone influenced period. It shows pathogenic bacterial counts were not much affected by the influence of cyclone Hud hud than it is hypothesized due to enhanced land-drainage.

3.4. Influence of winter on heterotrophic, indicator and pathogenic bacterial abundance and distribution in the coastal Bay of Bengal

Lower HB abundance was observed in the coastal stations due to the lower temperature in the water column (Fig. 5i) and low organic matter availability due to less discharge, weak vertical inputs of nutrients resulting in low phytoplankton production as evidenced by the Chl-*a* concentrations in the water column.

The occurrence of TC was observed in the upper 50m of the water column in the entire study region due to the discharge of sewage from Visakhapatnam City. The enhanced abundance of TC was observed in the offshore region due to fishing activity and shipping traffic. It is unclear why EC was observed only during winter in the upper 50 m depth water column (Fig. 6e). The relatively higher abundance of EF counts was observed in the coastal than offshore that could be due to the discharge of sewage (Fig. 6i). It shows that only TC and EF were negatively influenced by the low temperature, nutrients and organic matter off-shore.

AH counts were observed in only two off-shore sampling points (V4 0, 5 m) (Fig. 7a) might be due to fisherman activities. EA was abundant in the upper column from surface to around 50 m water column depth (Fig. 7i). PA was low and uniform thorough out the water column (Fig. 9a) during winter. This suggests the physical conditions (low temperature in the water column) (Fig. 2a) might influence the PA (optimum temperature for growth is 37 °C). VC and VV were observed in the upper 10 m of the water column in the coastal regions while they were gradually reduced towards off-shore (Fig. 9e). EC O157:H7, KP, VF and VP were not observed in the study region during winter. It shows pathogenic bacterial counts were not much affected by the influence of winter except PA, EA and VC.

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The strong positive relationship between Chl-*a* and bacterial abundance suggests that Chl-*a* plays a more important role in affecting bacterial growth (Lopez-Urrutia and Moran, 2007). Salinity is also an important parameter and can be considered as a proxy for freshwater discharge (including riverine discharge and precipitation) that delivers terrestrial organic matters and nutrients to the ocean. Organic matters within the Pearl River discharge can significantly stimulate bacterial biomass and respiration in coastal waters (Zhai et al., 2005). The decrease of bacterial abundance with increasing depth might result from the stimulatory effect of light on bacterial growth (Mary et al., 2008) or growth rate and excretion of dissolved organic matter of phytoplankton. It is also possible that grazers shift to selectively graze on heterotrophic bacteria in deeper waters as autotrophic preys become less abundant. Microbial community in the ocean encounter several physical and atmospheric events and their diversity, spatiotemporal distribution and abundance depends on several factors like progression of upwelling (Bergen et al., 2015, Coelho-Souza et al., 2013, Cury et al., 2011), mesoscale cyclonic eddy (Nelson et al., 2014, Zhang et al., 2009, 2011), cyclone (Neveux et al., 2009), nutrients and currents (Zeigler Allen et al., 2012), winter Ekman pumping (Doolittle et al., 2008), spring season (Larsen et al., 2004), across a river to ocean gradient (Crump et al., 2004, Fortunato et al., 2012), reefs, inlets and wastewater outfalls (Campbell et al., 2015).

The abundance of TC and EF was significantly influenced by coastal upwelling, cyclone (Hud hud) and winter. It seems from our studies that winter and upwelling enhanced the abundance of TC, but the cyclone Hud hud decreased. To our knowledge, there were no reports showing the variations of indicator bacteria abundance and distribution in the coastal marine waters during different physical and atmospheric events. An earlier study by Prasad et al. (2015) during monsoon also shows the highest counts in the coastal waters off Visakhapatnam city as this region was highly influenced by several anthropogenic activities, such as the use of beaches for recreational activities, discharges from ships, fishery activities, domestic and industrial sewage. The abundance of these indicator bacteria is consistent with the studies carried out in other habitats (Aayushi et al., 2014, Berna and Aysu, 2014, Clark et al., 2003, DebRoy et al., 2012, Knight, 2012, Nagvenkar and Ramaiah, 2009, Patra et al., 2009, Ramaiah et al., 2004, Robin et al., 2012, Rodrigues et al., 2011) but most of the earlier studies are either single sampling (whole study or multiple years during same period)/confined to coast, and no seasonal variation studies were studied.

This study suggested that there is no co-relation obtained on the effect of physical and atmospheric events on their abundance except that PA abundance was influenced by three different

physical events. Due to a sharp rise in the human settlement in the coastal zones, the surrounding aquatic environment, which is used for various activities such as fishing and recreation, are subjected to a rise in the distribution of human pathogenic microbial forms. The tendency of these bacteria entering the water is greater during monsoon owing to huge fresh water runoff. There are several potential explanations for the presence of indicator bacteria and the absence of pathogenic bacteria, or vice versa and there is no straight relationship among numbers of any indicator and enteric pathogens (Grabow, 1996). Pathogenic bacteria observed in the present study such as AH, EC O157:H7, EA, KP, SaT, Sh, PA, VC and VF were noticed wherever indicator bacteria observed. This suggests that pathogenic bacterial presence linked to the presence of indicator bacteria as both are coming from gut and part of the faeces, but not all faeces contain these organisms but come from diseased persons or carriers. Due to this reason they are not uniform in the water column. To our knowledge, there were no reports showing the variations of pathogenic bacterial abundance and distribution in the coastal waters during different physical and atmospheric events. But the abundance of these pathogenic bacteria is consistent with the studies carried out in other habitats (Aayushi et al., 2014, Araujo et al., 1991, Baffone et al., 2001, Barbieri et al., 1999, Berna and Aysu, 2014, Clark et al., 2003, DebRoy et al., 2012, Dumontet et al., 2000, Edun and Efiuvwevwere, 2012, Hatha et al., 2004, Hervio-Heath et al., 2002, Jeganathan et al., 2014, Kaper et al., 1981, Keene et al., 1994, Knight, 2012, Lokabharathi et al., 1987, Masini et al., 2007, Maugeri et al., 2006, Miyagi et al., 2001, Mukhopadhyay et al., 2008, Nagvenkar and Ramaiah, 2009, Nair et al., 1980, Patra et al., 2009, Pradeep and Lakshmanperumalsamy, 1986, Ramaiah et al., 2004, Ramaiah and Chandramohan, 1987, Robin et al., 2012, Rodrigues et al., 2011, Seidler et al., 1980, Stine et al., 2003, Williams et al., 2007).

Heterotrophic viable bacterial counts during different physical events showed significant variations with reference to physical and biogeochemical parameters in the study region. Water column temperature, Chl-*a*, turbidity, dissolved oxygen, ammonium, silicate and pH linearly correlated with HBC ($r^2 = 0.41, 0.27, 0.36, 0.28, 0.59, 0.33$ and $0.36, p < 0.001$) (Table 1), as high amounts of these are favorable for growth. Water column salinity and TSM inversely correlated with HBC ($r^2 = -0.27$ and $-0.45, p < 0.001$) (Table 1), as higher amounts of these negatively influence as the earlier will reduce the light penetration and effect photosynthesis resulting in low *in-situ* derived DOC. Turbidity and AHC linearly correlated with TCC ($r^2 = 0.34, p < 0.01; r^2 = 0.78, p < 0.001$) as high amounts of these are may be favorable for growth. Water column temperature, Chl-*a*, turbidity,

nitrite, nitrate and ECC linearly correlated with EFC ($r^2 = 0.43$, $p < 0.05$; $r^2 = 0.44$, $p < 0.05$; $r^2 = 0.36$, $p < 0.05$; $r^2 = 0.70$, $p < 0.001$; $r^2 = 0.71$, $p < 0.001$; $r^2 = 0.88$, $p < 0.05$) (Table 1), as high amounts of these are may be favorable for growth. Water column temperature, salinity, Chl-*a*, turbidity, dissolved oxygen, ammonium, nitrite, HBC, EFC and KPC linearly correlated with PAC ($r^2 = 0.33$, 0.51 , 0.31 , 0.45 , 0.47 , 0.61 , 0.35 , 0.42 , 0.53 and 0.88 , $p < 0.001$) (Table 1), as high amounts of these are may be favorable for growth. Ammonium and HBC linearly correlated with VVC ($r^2 = 0.74$, $p < 0.001$; $r^2 = 0.51$, $p < 0.05$) and HBC inversely correlated with VVC ($r^2 = -0.75$, $p < 0.001$).

4. Conclusions

Seasonal studies during different physical and atmospheric events on the west coast of the Bay of Bengal reveal that physical processes, such as winter, upwelling, monsoon and cyclone have significant impacts on nutrient cycling and phytoplankton biomass which further impacts the heterotrophic, indicator and pathogenic bacterial abundance in the water column. HBC showed significant temporal and spatial variations along the different stations near Visakhapatnam coastal waters due to diverse physical and biochemical phenomena. Higher HBC was noticed during intense upwelling and monsoon period due to increased availability of nutrients to the phytoplankton, which releases high dissolved organic matter that is the source for heterotrophic bacterial growth. IB abundance was noticed in the entire study area during winter, upwelling and monsoon seasons and after the cyclone, they were confined to coastal waters only with low abundance. Both TC and EF were influenced by the physical and biochemical phenomena. There is no clear correlation between abundance of IB and the presence of PB. But in this we found a clear correlation between both as in all sampling points where IB presence is noticed, PB presence also noticed but it is not uniform this suggests that not all faeces discharged to the coastal water either land derived or due to shipping traffic, fishermen activities in the sea. Coliforms, as well as other potentially pathogenic bacteria, were detected in high numbers in the entire study region during different periods. The presence of AH, EC O157:H7, EA, KP, SaT, Sh sp., PA, VC and VF in the coastal waters is alarming. Pollution of coastal water with untreated discharges and direct discharges by large ships and fishermen community resulting in the flourishing enteric bacteria which leads to the quality decline of marine

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wealth that pretence a human health menace and following a financial loss. This study reveals significant impacts of the physical and atmospheric forcing on the water column biogeochemistry and further on the phytoplankton, heterotrophic, indicator and pathogenic bacteria in the coastal Bay of Bengal. Further studies are required to examine how variations of such condition influence the coastal bacterial abundance and its impact on the other components of the ecosystem.

Acknowledgments

We thank the Director and Scientist-In-Charge, National Institute of Oceanography, for encouragement and support. This work is a part of the project PSC0105 funded by Council of Scientific and Industrial Research (CSIR). We appreciate the help of boat crew for their help during sampling. This is NIO contribution number XXXX.

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References

- Aayushi, M., Sunil, B., Rutuja, D., Gajbhiye, S.N., Dastager Syed G., 2014. Occurrence and distribution of multiple antibiotic-resistant bacteria of *Enterobacteriaceae* family in waters of Veraval coast, India. *Env. Exp. Biol.* 12, 43–50.
- Araujo, R.M., Arribas, R.M., Pares, R., 1991. Distribution of *Aeromonas* species in waters with different levels of pollution. *J. Appl. Bacteriol.* 71, 182–186.

- | Baffone, W., Citterio, B., Vittoria, E., Casaroli, A., Capana, R., Bruscolini, F., 2001. Determination of several potential virulence factors in *Vibrio* spp. Isolated from sea waters. *Food Microbiol.* 18, 479–488.
- | Bak, R.P.M., Nieuwland, G., 1993. Patterns in pelagic and benthic nanoflagellate densities in the coastal *upwelling* system along the Banc d'Arguin, Mauritania. *Hydrobiologia* 258, 119–131.
- | Barbieri, E., Falzano, L., Fiorentini, C., Pianetti, A., Baffone, W., Fabbri, A., Matarrese, P., Casiere, A., Katouli, M., Kühn, I., Möllby, R., Bruscolini, F., Donellig, 1999. Occurrence, diversity, and pathogenicity of halophilic *Vibrio* spp. and non-O1 *Vibrio cholerae* from estuarine waters along the Italian Adriatic coast. *Appl. Environ. Microbiol.* 65, 2748–2753.
- | Berg, G., 1978. The indicator system. In *Indicators of Viruses in Water and Food* (ed. G. Berg), pp. 1–13, Ann Arbor Science Publishers, Ann Arbor, MI.
- | Bergen, B., Herlemann, D.P., Jürgens, K., 2015. Zonation of bacterioplankton communities along aging upwelled water in the northern Benguela upwelling. *Front. Microbiol.* 6, 621.
- | Berna, K., Aysu, B., 2014. The occurrence of enteric bacteria in marine environment and pollution. *Mar. Sci. Tech. Bull.* 3, 39–43.
- | Campbell, A.M., Fleisher, J., Sinigalliano, C., White, J.R., Lopez, J.V., 2015. Dynamics of marine bacterial community diversity of the coastal waters of the reefs, inlets, and wastewater outfalls of southeast Florida. *Microbiol.* 4, 390–408.
- | Carritt, D.E., Carpenter, J.H., 1966. Comparison and evaluation of currently employed modifications of winkler method for determining dissolved oxygen in seawater—A Nasco report. *J. Mar. Res.* 24, 286–318.
- | Clark, A., Turner, T., Dorothy, K.P., Goutham, J., Kalavati, C., Rajanna, B., 2003. Health hazards due to pollution of waters along the coast of Visakhapatnam, east coast of India. *Ecotox. Environ. Safe.* 56, 390–397.
- | Coelho-Souza, S.A., Pereira, G.C., Coutinho, R., Guimarães, J.R., 2013. Yearly variation of bacterial production in the Arraial do Cabo protection area (Cabo Frio upwelling region): An evidence of anthropogenic pressure. *Braz. J. Microbiol.* 44, 1349–1357.
- | Crump, B.C., Hopkinson, C.S., Sogin, M.L., Hobbie, J.E., 2004. Microbial Biogeography along an Estuarine Salinity Gradient: Combined Influences of Bacterial Growth and Residence Time. *Appl. Environ. Microbiol.* 70, 1494–1505.
- | Cuevas, L.A., Daneri, G., Jacob, B., Montero, P., 2004. Microbial abundance and activity in the seasonal upwelling area off Concepción (~36°S), central Chile: a comparison of upwelling and non-upwelling conditions. *Deep-Sea Res. II.* 51, 2427–2440.
- | Cury, J.C., Araujo, F.V., Coelho-Souza, S.A., Peixoto, R.S., Oliveira, J.A., Santos, H.F., Dávila, A.M., Rosado, A.S., 2011. Microbial Diversity of a Brazilian Coastal Region Influenced by an Upwelling System and Anthropogenic Activity. *PLoS ONE* 6, e16553.

- | DebRoy, S., Das, S., Ghosh, S., Banerjee, S., 2012. Isolation of Nitrate and Phosphate Removing Bacteria from Various Environmental Sites. *OnLine J. Biol. Sci.* 12, 62–71.
- | Delesalle, B., Pichon, M., Frankignoulle, M., Gattuso, J.P., 1993. Effects of a cyclone on coral reef phytoplankton biomass, primary production and composition (Moorea Island, French Polynesia). *J. Plankton Res.* 15, 1413–1423.
- | Doolittle, D.F., Li, W.K.W., Wood, A.M., 2008. Winter time abundance of picoplankton in the Atlantic sector of the Southern Ocean. *Nova Hedwigia, Beiheft* 133, 147–160.
- | Dumontet, S., Krovacek, K., Svenson, S.B., Pasquale, V., Baloda, S.B., Figliuolo, D., 2000. Prevalence and diversity of *Aeromonas* and *Vibrio* spp. in coastal waters of Southern Italy. *Comp. Immunol. Microbiol. Infect. Dis.* 23, 53–72. doi: 10.1016/S0147-9571(99)00059-4.
- | Edun, O.M., Efiuvwevwere, B.J.O., 2012. Bacterial Profiles and Physico-chemical Parameters of Water Samples from Different Sites of the New Calabar River, Nigeria. *Sust. Agr. Res.* 1, 163–169.
- | Fortunato, C.S., Herfort, L., Zuber, P., Baptista, A.M., Crump, B.C., 2012. Spatial variability overwhelms seasonal patterns in bacterioplankton communities across a river to ocean gradient. *ISME J.* 6, 554–563.
- | Furnas, M.J., 1989. Cyclonic disturbance and a phytoplankton bloom in a tropical shelf ecosystem. In: Okaichi, T., Anderson, D.M., Nemoto, T. (eds) *Red tides: biology, environmental science, and toxicology*. Elsevier Science Publishing CO, New York, p 273–276.
- | Goldman, J.C., 1988. Spatial and temporal discontinuities of biological processes in pelagic surface waters. In: Rothschild, B.J. (ed) *Toward a theory on biological-physical interactions in the world ocean*. Kluwer Academic Publishers, Dordrecht, p 273–296.
- | Gomes, H.R., Goes, J.I., Saino, T., 2000. Influence of physical processes and freshwater discharge on the seasonality of phytoplankton regime in the Bay of Bengal. *Cont. Shelf. Res.* 20, 313–330.
- | Grabow, W.O.K., 1996. Waterborne diseases: Update on water quality assessment and control. *Water SA* 22, 193–202.
- | Grasshoff, K., Ehrhardt, M., Kremling, K., (eds) 1983. *Methods of Seawater Analysis*. Chemie, Weinheim, pp. 89–224.
- | Hanson, R.B., Alvarez-Ossorio, M.T., Cal, R., Campos, M.J., Roman, M., Santiago, G., Varela, M., Yoder, J.A., 1986. Plankton response following a spring upwelling event in the Ria de Arosa, Spain. *Mar. Ecol. Prog. Ser.* 32, 101–111.
- | Hatha, A.A.M., Abhirosh, C., Mujeeb Rahiman, K.M., 2004. Prevalence of diarrhegenic serotypes of *Escherichia coli* in the Cochin estuary, along west coast of India. *Ind. J. Mar. Sci.* 33, 238–242.

- Hervio-Heath, D., Colwell, R.R., Derrien, A., Robert-Pillot, A., Fournier, J.M., Pommepey, M., 2002. Occurrence of pathogenic vibrios in coastal areas of France. *J. Appl. Microbiol.* 92, 1123–1135. doi: 10.1046/j.1365-2672.2002.01663.x.
- Jeganathan, P., Rajasekaran, K.M., Asha Devi, N.K., 2014. Antimicrobial activity and Characterization of Marine bacteria in Coastal sea water. *Sch. Acad. J. Pharm.* 3, 73–78.
- Kaper, J.B., Lockman, H., Colwell R.R., Joseph, S.W., 1981. *Aeromonas hydrophila*: ecology and toxigenicity of isolates from an estuary. *J. Appl. Bacteriol.* 50, 359–377.
- Keene, W.E., McAnulty, J.M., Hoestly, F.C., Williams, L.P., Jr, Hedber, K., Oxman, G.L., Barrett, T.J., Pfaller, M.A., Fleming, D.W., 1994. A swimming-associated outbreak of hemorrhagic colitis caused by *Escherichia coli* O157:H7 and *Shigella sonnei*. *N. Engl. J. Med.* 331, 579–584.
- Knight, M., 2012. The introduction and dissemination of pathogenic bacteria in the Pacific coastal waters of southern California and Mexico. *Oceanography Senior Thesis Symposium.*
- Larsen, A., Flaten, G.A.F., Sandaa, R.-A., Castberg, T., Thyraug, R., Erga, S.R., Jacquet, M.S., Bratbak, G., 2004. Spring phytoplankton bloom dynamics in Norwegian coastal waters: Microbial community succession and diversity. *Limnol. Oceanogr.* 49, 180–190.
- LokaBharathi, P.A., Nair, S., Chadramohan, D., 1987. Occurrence and distribution of *Vibrio parahaemolyticus* and related organisms in Arabian Sea. *Mahasagar Bull. Natl. Inst. Oceanogr.* 20, 43–51.
- Madhu, N.V., Maheswaran, P.A., Jyothibabu, R., Sunil, V., Revichandran, C., Balasubramanian, T., Gopalakrishnan, T.C., Nair, K.K.C., 2002. Enhanced biological production off Chennai triggered by October 1999 super cyclone Orissa. *Curr. Sci.* 82, 1472–1479.
- Maneesha, K., Sarma, V.V.S.S., Reddy, N.P.C., Sadhuram, Y., Ramana Murty, T.V., Sarma, V.V., Kumar, M.D., 2011. Meso-scale atmospheric events promote phytoplankton blooms in the coastal Bay of Bengal. *J. Earth. Syst. Sci.* 120, 1–10.
- Mangesh, G., Siby, K., Damodar, S.M., Hema, N., Naqvi, S.W.A., 2016. Cyclone Phyan-induced plankton community succession in the coastal waters off Goa, India. *Cur. Sci.* 111, 1091–1097.
- Mary, I., Tarran, G.A., Warwick, P.E., Terry, M.J., Scanlan, D.J., Burkill, P.H., Zubkov, M.V., 2008. Light enhanced amino acid uptake by dominant bacterioplankton groups in surface waters of the Atlantic Ocean. *FEMS Microbiol. Ecol.* 63, 36–45.
- Masini, L., De Grandis, G., Principi, F., Mengarelli, C., Ottaviani, D., 2007. Research and characterization of pathogenic vibrios from bathing water along the Conero Riviera (Central Italy). *Water Res.* 41, 4031–4040. doi: 10.1016/j.watres.2007.05.003.
- Maugeri, T.L., Carbone, M., Fera, M.T., Gugliandolo, C., 2006. Detection and differentiation of *Vibrio vulnificus* in seawater and plankton of a coastal zone of the Mediterranean Sea. *Res. Microbiol.* 157, 194–200. doi: 10.1016/j.resmic.2005.06.007.

- | McManus, G.B., Peterson, W.T., 1988. Bacterioplankton production in the nearshore zone during upwelling off central Chile. *Mar. Ecol. Prog. Ser.* 43, 11–17.
- | Miyagi, K., Omura, K., Ogawa, A., Hanafusa, M., Nakano, Y., Morimatsu, S., Sano, K., 2001. Survival of shiga toxin-producing *Escherichia coli* O157 in marine water and frequent detection of the Shiga toxin gene in marine water samples from an estuary port. *Epidemiol. Infect.* 126, 129–133.
- | Mukhopadhyay, C., Chawla, K., Sharma, Y., Bairy, I., 2008. Emerging extra-intestinal infections with *Aeromonas hydrophila* in coastal region of southern Karnataka. *J. Postgraduate Med.* 54, 199–202.
- | Nagvenkar, G.S., Ramaiah, N., 2009. Abundance of sewage-pollution indicator and human pathogenic bacteria in a tropical estuarine complex. *Environ. Monit. Assess.* 155, 245–256. doi: 10.1007/s10661-008-0432-1.
- | Nair, G.B., Abraham, M., Natarajan, R., 1980. Marine Vibrios and related genera from the velar estuary. *Mahasagar Bull. Natl. Inst. Oceanogr.* 13, 285–290.
- | Nayak, S.R., Sarangi, R.K., Rajawat, A.S., 2001, Application of IRS-P4 OCM data to study the impact of cyclone on coastal environment of Orissa. *Curr. Sci.* 80, 1208–1213.
- | Nelson, C.E., Carlson, C.A., Ewart, C.S., Halewood, E.R., 2014. Community differentiation and population enrichment of Sargasso Sea bacterioplankton in the euphotic zone of a mesoscale mode-water eddy. *Environ. Microbiol.* 16, 871–887.
- | Neveux, J., Tenório, M.M.B., Jacquet, S., Torrétón, J.-P., Douillet, P., Ouillon, S., Dupouy, C., 2009. Chlorophylls and Phycoerythrins as Markers of Environmental Forcings Including Cyclone Erica Effect (March 2003) on Phytoplankton in the Southwest Lagoon of New Caledonia and Oceanic Adjacent Area. *Int. J. Ocean.* 2009. 1-19. doi:10.1155/2009/232513.
- | Nicholas J. Ashbolt., Willie O.K. Grabow., Mario Snozzi., 2001. Indicators of microbial water quality. WHO. *Water Quality: Guidelines, Standards and Health*. Edited by Lorna Fewtrell and Jamie Bartram. Published by IWA Publishing, London, UK. ISBN: 1 900222 28 0
- | Patra, A.K., Acharya, B.C., Mohapatra, A., 2009. Occurrences and distribution of bacterial indicator and pathogens in coastal waters of Orissa. *Ind. J. Mar. Sci.* 38, 474–480.
- | Patti, A.M., Paroli, E., Gabrieli, R., D' Angelo, A.M., De-Filippis, P., Villa, L., Pana, A., 1987. Enteroviruses recovery from seawater: Statistical correlation with usual and chemical parameters, *Ig. Mod.* 87, 226–243.
- | Piccolomini, R., Cellini, L., Allocati, N., Gentili, E., Sartorelli, M., Di-Girolamo, A., 1987. Microbiological pollution of seawater, *Ig. Mod.* 87, 543–552.
- | Piontkovski, S.A., Al-Hashmi, S.A., 2014. Atmospheric cyclones and seasonal cycles of biological productivity of the ocean. *Int. J. Env. Stu.* 71, 27–40.

- | Pradeep, R., Lakshmanperumalsamy, P., 1986. Distribution of fecal indicator bacteria in Cochin backwater. *Ind. J. Mar. Sci.* 15, 99–101.
- | Prasad, V.R., Srinivas, T.N.R., Sarma, V.V.S.S., 2015. Influence of river discharge on abundance and dissemination of heterotrophic, indicator and pathogenic bacteria along the east coast of India. *Mar. Poll. Bull.* 95, 115–125.
- | Prasanna Kumar, S., Muraleedharan, P.M., Prasad, T.G., Gauns, M., Ramaiah, N., de Souza, S.N., Madhupratap, M., 2002. Why is the Bay of Bengal less productive during summer monsoon compared to the Arabian Sea? *Geophys. Res. Lett.* 29, 2235. doi:10.1029/2002GL016013.
- | Ramaiah, N., Chandramohan, D., 1987. Distribution and species composition of planktonic luminous bacteria in the Arabian Sea. *Ind. J. Mar. Sci.* 16, 139–142.
- | Ramaiah, N., Kolhe, V., Sadhasivan, A., 2004. Abundance of pollution indicator and pathogenic bacteria in Mumbai waters. *Curr. Sci.* 87, 435–439.
- | Robin R.S., Vishnu Vardhan, K., Muduli, P.R., Srinivasan, M., Balasubramanian, T., 2012. Preponderance of Enteric Pathogens Along the Coastal Waters of Southern Kerala, Southwest Coast of India. *Mar. Sci.* 2, 6–11. doi:10.5923/j.ms.20120201.02.
- | Rodrigues, V., Ramaiah, N., Kakti, S., Samant, D., 2011. Long-term variations in abundance and distribution of sewage pollution indicator and human pathogenic bacteria along the central west coast of India. *Ecol. Indic.* 11, 318–327. doi:10.1016/j.ecolind.2010.05.010.
- | Rozen, Y., Belkin, S., 2001. Survival of enteric bacteria in seawater. *FEMS Microbiol. Rev.* 25, 513–529.
- | Sarma, V.V.S.S., Krishna, M.S., Viswanadham, R., Rao, G.D., Rao, V.D., Sridevi, B., Kumar, B.S.K., Prasad, V.R., Subbaiah, Ch.V., Acharyya, T., Bandopadhyay, D., 2013. Intensified oxygen minimum zone on the western shelf of Bay of Bengal during summer monsoon: influence of river discharge. *J. Oceanogr.* 69, 45–55. doi:10.1017/s10872-012-0156-2.
- | Seidler, R.J., Allen, D.A., Lockman, H., Colwell, R.R., Joseph, S.W., Daily, O.P., 1980. Isolation, enumeration and characterization of *Aeromonas* from polluted waters encountered in diving operations. *Appl. Environ. Microbiol.* 39, 1010–1018.
- | Sorokin, Yu. I., 1981. Microheterotrophic organisms in marine ecosystems. In Longhurst, A. (ed.) *Analysis of Marine Ecosystems*. Academic Press, New York, pp. 243–342.
- | Sorokin, Y. I., Kogelschatz, J. E., 1979. Analysis of heterotrophic microplankton in an upwelling area. *Hydrobiologia* 66, 195–208.
- | Stine, O.C., Carnahan, A., Singh, R., Powell, J., Furuno, J.P., Dorsey, A., Silbergeld, E., Williams, H.N., Morris, J.G., 2003. Characterization of microbial communities from coastal waters using microarrays. *Environ. Monit. Assess.* 81, 327–336.
- | Suzuki, R., Ishimaru, T., 1990. An improved method for the determination of phytoplankton chlorophyll using N, N-dimethylformamide. *J. Oceanogr.* 46, 190–194.

- | Taylor, G.T., 1989. Variability in the vertical flux of microorganisms and biogenic material in the epipelagic zone of a North Pacific central gyre station. *Deep Sea Res.* 36, 1287–1308.
- | Tenore, K.R., Alonso-Noval, M., Álvarez-Ossorio, M.T., Atkinson, A., Cabanas, J.M., Cal, R.M., Campos, H.J., Castillejo, F., Chesney, E.J., González, N., Hanson, R.B., McClain, C.R., Miranda, A., Roman, M.R., Sánchez, J., Santiago, G., Valdés, J.L., Varela, M., Yoder, M., 1995. Fisheries and oceanography off Galicia, NW Spain: mesoscale spatial and temporal changes in physical processes and resultant patterns of biological productivity. *J. Geophys. Res.* 100, 10943–10996.
- | Troncoso, V.A., Daneri, G., Cuevas, L.A., Jacob, B., Montero, P., 2003. Bacterial carbon flow in the Humboldt Current System off Chile. *Mar. Ecol. Prog. Ser.* 250, 1–12.
- | Varkey, M.J., Murty, V.S.N., Suryanarayana, A., 1996. Physical oceanography of the Bay of Bengal and Andaman Sea. *Oceanogr. Mar. Biol. Ann. Rev.* 34, 1–70.
- | Williams, A.P., Avery, L.M., Killham, K., Jones, D.L., 2007. Persistence, dissipation, and activity of *Escherichia coli* O157:H7 within sand and seawater environments. *FEMS Microbiol. Ecol.* 60, 24–32.
- | Zeigler Allen, L., Allen, E.E., Badger, J.H., McCrow, J.P., Paulsen, I.T., Elbourne, L.D., Thiagarajan, M., Rusch, D.B., Nealson, K.H., Williamson, S.J., Venter, J.C., Allen, A.E., 2012. Influence of nutrients and currents on the genomic composition of microbes across an upwelling mosaic. *ISME J.* 6, 1403–1414.
- | Zhai, W., Dai, M., Cai, W.-J., Wang, Y., Wang, Z., 2005. High partial pressure of CO₂ and its maintaining mechanism in a subtropical estuary: the Pearl River estuary, China. *Mar. Chem.* 93, 21–32.
- | Zhang, Y., Sintés, E., Chen, J. N., Zhang, Y., Dai, M. H., Jiao, N. Z., Herndl, G.J., 2009. Role of mesoscale cyclonic eddies in the distribution and activity of Archaea and Bacteria in the South China Sea. *Aquat. Microb. Ecol.* 56, 65–79.
- | Zhang, Y., Jiao, N., Sun, Z., Hu, A., Zheng, Q., 2011. Phylogenetic diversity of bacterial communities in South China Sea mesoscale cyclonic eddy perturbations. *Res. Microbiol.* 162, 320–329.

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Legends to the Figures:

Fig. 1. Sampling locations of the time-series stations, off Visakhapatnam, in the east coast of India.

- Fig. 2.** Distribution of (a to d) temperature ($^{\circ}\text{C}$), (e to h) salinity (psu), (i to l) Chlorophyll (mg/m^3) during four different months corresponding to winter, spring, summer and post-monsoon seasons in the east coast of India.
- Fig. 3.** Distribution of (a to d) turbidity (NTU), (e to h) total suspended mater (g/l), (i to l) dissolved oxygen (μM) during four different months corresponding to winter, spring, summer and post-monsoon seasons in the east coast of India.
- Fig. 4.** Distribution of (a to d) ammonium (μM), (e to h) nitrate (μM), (i to l) phosphate (μM) during four different months corresponding to winter, spring, summer and post-monsoon seasons in the east coast of India.
- Fig. 5.** Distribution of (a to d) pH, (e to h) total alkalinity, (i to l) heterotrophic bacteria counts (CFU ml^{-1}) during four different months corresponding to winter, spring, summer and post-monsoon seasons in the east coast of India.
- Fig. 6.** Distribution of indicator bacteria (a to d) total coliforms (CFU ml^{-1}), (e to h) *Escherichia coli* counts (CFU ml^{-1}), (i to l) *Enterococcus faecalis* counts (CFU ml^{-1}) during four different months corresponding to winter, spring, summer and post-monsoon seasons in the east coast of India.
- Fig. 7.** Distribution of pathogenic bacteria (a to d) *Aeromonas hydrophila* counts (CFU ml^{-1}), (e to h) *Escherichia coli* O157:H7 counts (CFU ml^{-1}), (i to l) *Enterobacter aerogenes* counts (CFU ml^{-1}) during four different months corresponding to winter, spring, summer and post-monsoon seasons in the east coast of India.
- Fig. 8.** Distribution of pathogenic bacteria (a to d) *Klebsiella pneumoniae* counts (CFU ml^{-1}), (e to h) *Salmonella typhi* counts (CFU ml^{-1}), (i to l) *Shigella* sp. counts (CFU ml^{-1}) during four different months corresponding to winter, spring, summer and post-monsoon seasons in the east coast of India.
- Fig. 9.** Distribution of pathogenic bacteria (a to d) *Pseudomonas aeruginosa* counts (CFU ml^{-1}), (e to h) *Vibrio cholerae* counts (CFU ml^{-1}), (i to l) *Vibrio fluvialis* counts (CFU ml^{-1}) during winter, spring, summer and post-monsoon periods in the east coast of India.

Table 1. Rank correlation matrix (Spearman's rs) of biogeochemical parameters measured in off Visakhapatnam marine waters of east coast of India.

	Temp	Sal	Chl	Turb	TSM	DO	NH ₄ ⁺	NO ₂ ⁻	PO ₄ ³⁻	SiO ₄ ⁴⁻	NO ₃ ⁻	pH	TA
Temp	1.00												
Sal	-0.28	1.00											
Chl	0.14	0.12	1.00										
Turb	0.09	<u>0.23</u>	0.57	1.00									
TSM	-0.15	0.58	-0.01	-0.02	1.00								
DO	0.38	-0.33	<i>0.20</i>	0.06	-0.38	1.00							
NH ₄ ⁺	0.38	<u>-0.24</u>	0.08	<i>0.19</i>	-0.58	0.31	1.00						
NO ₂ ⁻	0.03	0.46	0.37	0.37	0.25	<i>-0.25</i>	0.13	1.00					
PO ₄ ³⁻	0.06	-0.45	<i>-0.19</i>	-0.14	-0.63	0.00	0.31	-0.46	1.00				
SiO ₄ ⁴⁻	<u>0.26</u>	-0.40	0.15	0.09	-0.16	<u>-0.27</u>	<i>0.21</i>	0.02	<i>0.20</i>	1.00			
NO ₃ ⁻	-0.30	0.65	0.29	0.48	0.44	-0.54	<i>-0.20</i>	0.60	-0.36	0.04	1.00		
pH	0.30	-0.67	0.11	-0.02	-0.60	0.68	0.44	-0.24	0.35	0.09	-0.61	1.00	
TA	<u>-0.25</u>	0.80	0.13	0.19	0.54	-0.32	-0.41	<u>0.28</u>	-0.38	-0.43	0.55	-0.42	1.00
HB	0.41	-0.27	0.27	0.36	-0.45	0.28	0.59	0.10	0.18	0.33	-0.12	0.36	-0.42
AH	0.10	-0.20	0.35	<i>0.55</i>	0.36	0.10	-0.49	0.18	-0.23	0.20	0.10	0.18	-0.13
TC	0.19	0.23	0.22	<u>0.34</u>	0.18	-0.04	-0.08	0.19	0.04	0.02	0.19	-0.15	<i>0.27</i>
EC	-0.19	-0.17	-0.10	-0.02	-0.03	0.17	0.17	-0.04	0.48	-0.37	0.05	0.07	-0.20
EC157	<i>-0.60</i>	<i>0.66</i>	0.14	0.49	-0.28	<i>-0.57</i>	0.13	0.33	-0.05	-0.10	0.56	<i>-0.65</i>	0.47
EA	-0.01	-0.34	-0.06	-0.02	-0.20	0.24	-0.07	-0.12	<i>0.47</i>	-0.05	-0.11	0.29	-0.27
EF	<i>0.43</i>	0.49	<i>0.44</i>	<i>0.36</i>	-0.39	0.32	0.08	0.70	-0.35	-0.31	0.71	-0.17	0.35
KP	0.40	-0.27	0.23	-0.14	-0.34	0.16	-0.05	0.67	0.23	-0.36	-0.10	0.40	-0.21
P	0.33	0.51	0.31	0.45	0.02	0.47	0.61	0.35	-0.13	-0.36	0.13	0.12	0.35
Sa	0.08	-0.05	-0.53	-0.12	0.41	-0.19	-0.23	-0.80	0.15	0.77	0.14	0.09	-0.18
Sh	0.25	-0.25	-0.54	0.40	-0.04	-0.25	0.06	--	0.55	--	0.26	0.27	-0.41
V	0.24	-0.15	0.38	-0.13	--	0.26	0.44	0.38	-0.12	-0.02	-0.29	0.18	0.32
VC	-0.49	-0.40	0.01	0.22	-0.52	0.38	0.74	-0.23	0.52	-0.35	-0.07	0.19	-0.75
VF	0.21	-0.32	0.95	0.63	0.95	0.63	-0.74	0.87	-0.74	0.32	1.00	0.95	0.32
VV	-0.49	-0.40	0.01	0.22	-0.52	0.38	0.74	-0.23	0.52	-0.35	-0.07	--	--

Table 1 contd.

	HB	AH	TC	EC	EC157	EA	EF	KP	P	Sa	Sh	V	VC	VF	VV
HB	1.00														
AH	0.26	1.00													
TC	0.06	0.78	1.00												
EC	-0.03	-0.50	0.21	1.00											
EC157	0.20	-1.00	0.45	-0.39	1.00										
EA	0.07	--	0.40	1.00	-0.39	1.00									
EF	-0.01	--	0.03	<i>0.88</i>	--	0.13	1.00								
KP	0.41	--	-0.87	--	--	--	0.00	1.00							
P	0.42	0.00	0.26	0.24	0.48	0.00	0.53	0.88	1.00						
Sa	-0.15	--	-0.72	--	--	--	--	--	-0.04	1.00					
Sh	0.03	--	-0.40	--	--	--	--	--	0.04	1.00	1.00				
V	-0.03	--	0.74	--	--	-0.87	-0.03	--	0.27	--	--	1.00			
VC	0.51	-0.50	-0.19	0.38	-0.35	0.38	0.26	--	0.26	--	--	--	1.00		
VF	0.11	0.63	0.50	--	--	--	--	--	--	--	--	--	--	1.00	
VV	<i>0.51</i>	-0.50	-0.19	0.38	-0.35	0.38	0.26	--	0.26	--	--	--	1.00	--	1.00

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TEMP, temperature; SAL, salinity; CHL, chlorophyll; TURB, turbidity; TSM, total suspended matter; DO, dissolved oxygen; NH₄⁺, ammonium; NO₂⁻, nitrite; PO₄³⁻, phosphate; SiO₄⁴⁻, silicate; NO₃⁻, nitrate; TA, total alkalinity; HB, heterotrophic bacterial; AH, *Aeromonas hydrophila*; TC, total coliform; EC, *Escherichia coli*; EC157, *Escherichia coli* O157:H7; EA, *Enterobacter aerogenes*; EF, *Enterococcus faecalis*; KP, *Klebsiella pneumoniae*; PA, *Pseudomonas aeruginosa*; SaT, *Salmonella typhi*; Sh, *Shigella*; V, *Vibrio*; VC, *Vibrio cholerae*; VF, *Vibrio fluvialis*; VV, *Vibrio vulnificus*.

*** **P < 0.001 (Bold)**; ** P < 0.01 (Underline); * *P < 0.05 (Italic)*.

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Fig. 1
24

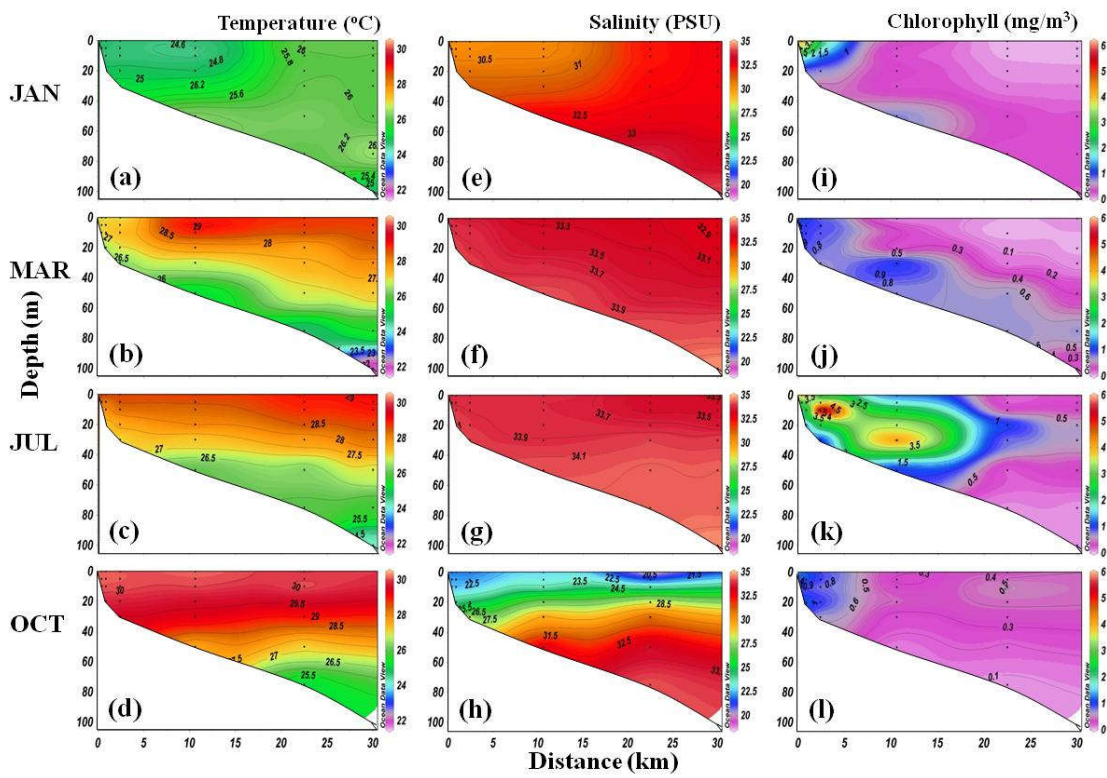


Fig. 2

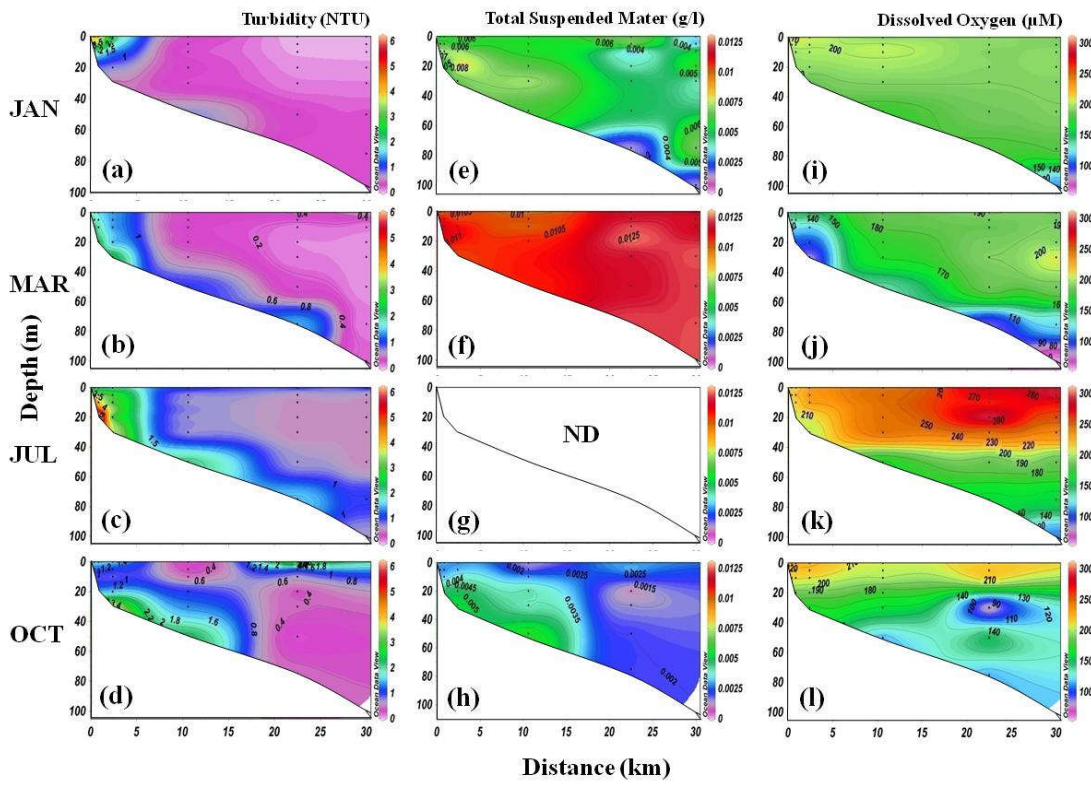


Fig. 3

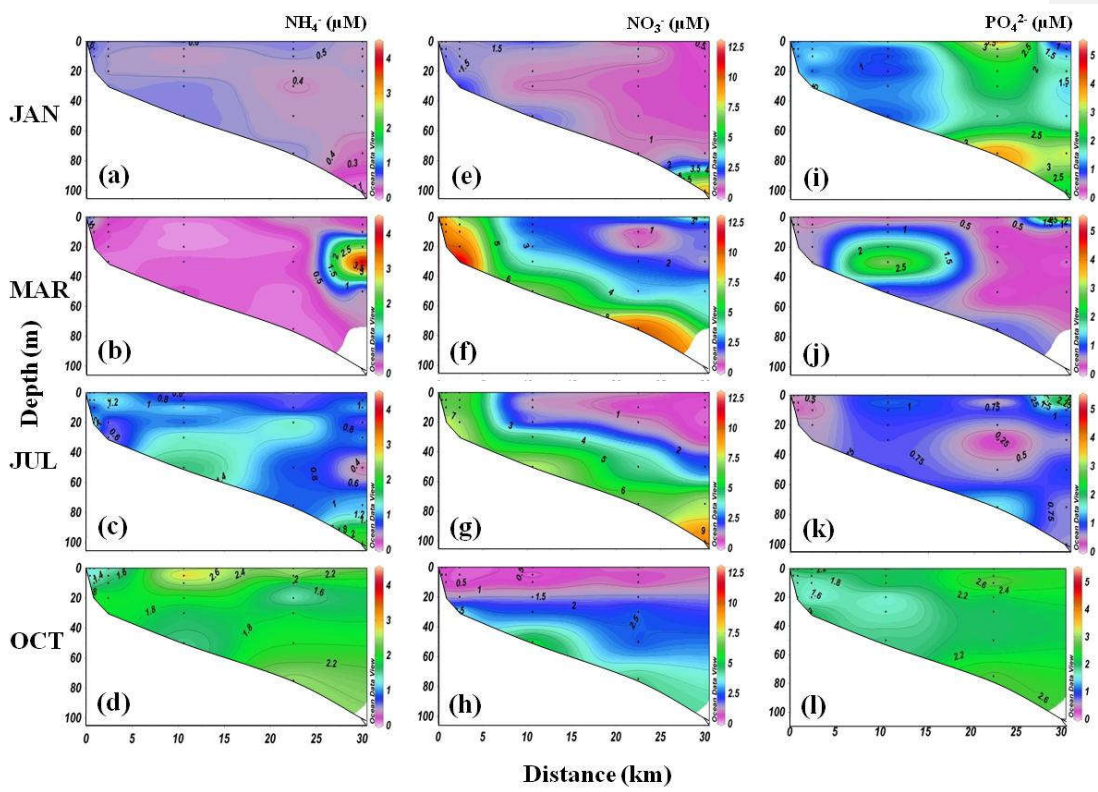


Fig. 4

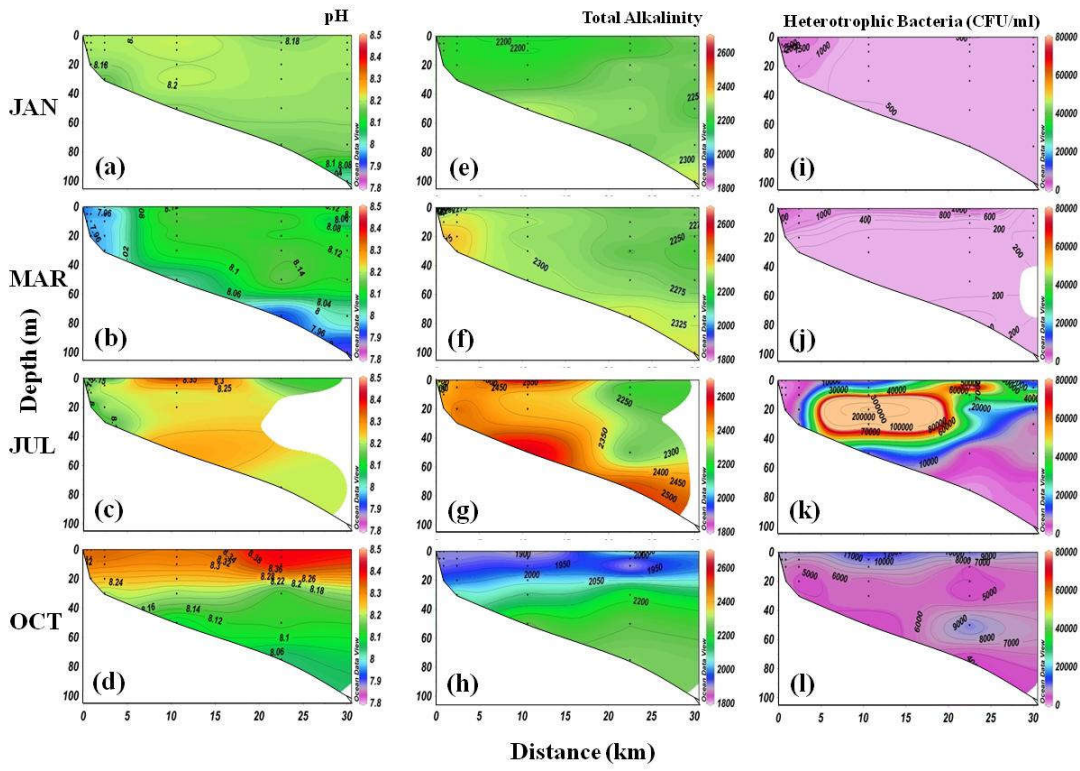


Fig. 5

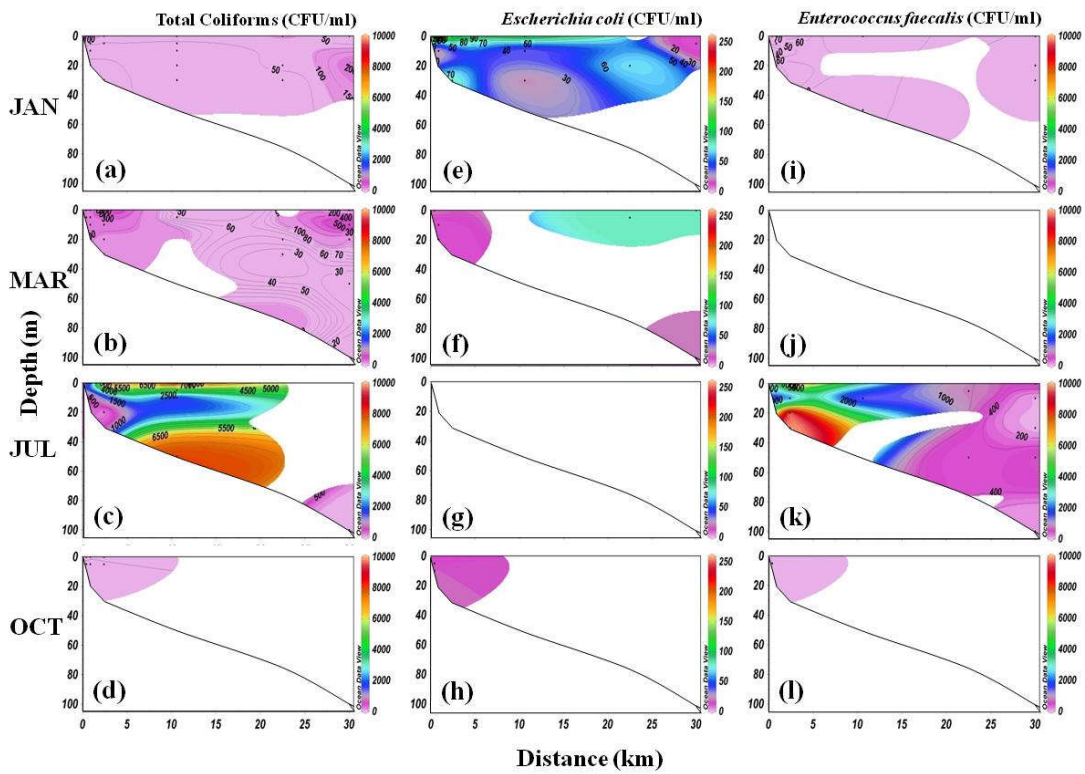


Fig. 6

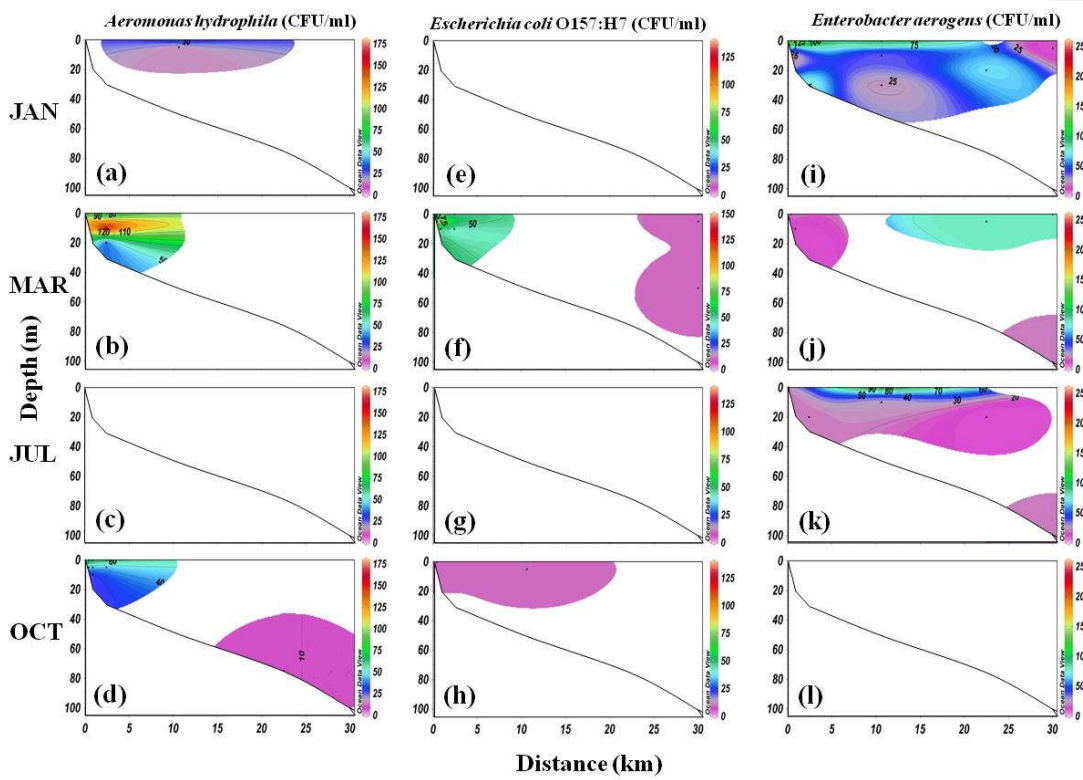


Fig. 7

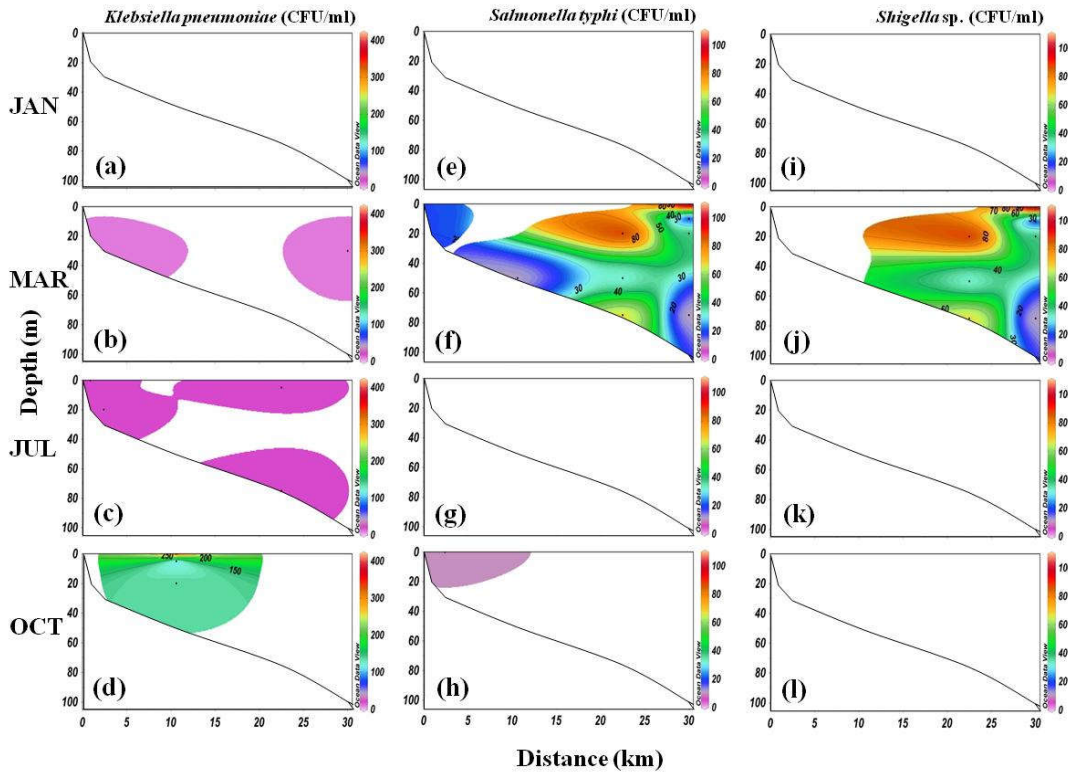


Fig. 8

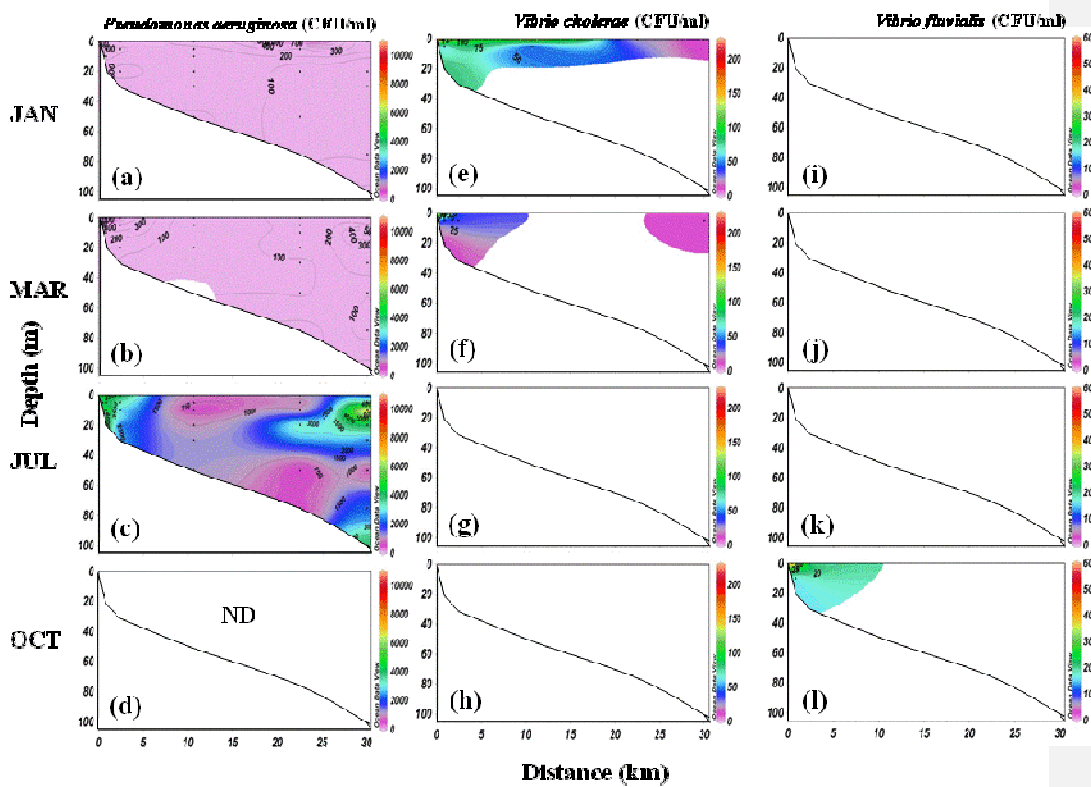


Fig. 9