

Roles of upwelling and riverine influx on the summer phytoplankton bloom in the Western Bay of Bengal.

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Abstract

The Bay of Bengal (BoB) is generally considered a low-productive region. However, several phytoplankton blooms (high Chlorophyll *a*) are frequently reported, including the one observed between Kakinada (KKD) and Visakhapatnam (VSKP) during the Southwest Monsoon (SWM) of 2019. Hydrographic observations along the two adjacent cross-shore sections of Visakhapatnam (VSKP) and Kakinada (KKD) revealed the presence of different water masses in these regions. VSKP transect was influenced by intense coastal upwelling that advected towards the slope and offshore area. In contrast, the coastal and slope locations of the KKD transect was dominantly influenced by the Godavari River input, while there was a warm-core eddy in the offshore region. There was an increase in the Chlorophyll *a* (Chl *a*) biomass in the coastal locations of KKD (4.37 ± 2.04 mg/m³) caused by the freshwater input, but the magnitude was substantially high in the coastal and slope regions of VSKP (8.52 ± 2.86 mg/m³) extending further towards offshore associated with upwelling and their advection processes. Column integrated Chl *a* concentration was 2-3 folds higher in the offshore regions of VSKP due to the presence of subsurface Chl *a* Maxima (SSCM), while it was absent in KKD. Based on the vertical patterns of the Chl *a*, the present study could observe two less known patterns in the distribution of Chl *a*, such as (1) double Chl *a* maxima (DoCM) and (2) extended Chl *a* maxima (ECM). This study elaborates on the coastal and oceanic processes causing the change in the hydrography leading to the development of massive surface blooms and their distinct vertical patterns in the WBoB.

Keywords: Phytoplankton biomass; Upwelling; Riverine influx; Bay of Bengal

1. Introduction

The Bay of Bengal (BoB) upper layer is generally considered an oligotrophic region (Madhupratap et al., 1996; Prasannakumar et al., 2002; Gauns et al., 2005) due to nutrient limitation caused by salinity stratification. However, previous in-situ measurements, satellite imagery and ocean modelling studies revealed several hot spots of high Chlorophyll *a* (Chl *a*) in the coastal and offshore regions of BoB (Vinayachandran et al., 1999; Gomes et al., 2000; Vinayachandran, 2009; Jyothibabu et al., 2015; Thushara and Vinayachandran et al., 2016; Bharathi et al., 2018). High phytoplankton biomass in coastal waters was reported in upwelling sites, locations near the freshwater runoff and the advection path low saline waters in the BoB (Gomes et al., 2000; Vinayachandran et al., 2009; Baliarsingh et al., 2015 and 2016; Bharathi et al., 2018; Amol et al., 2019; Jagadeesan et al., 2021). In open ocean regions, high phytoplankton biomass was reported along the path of the cyclone, extreme events and advection path of summer monsoonal current (Madhu et al., 2002; Vinayachandran and Mathew, 2003; Prasanna Kumar et al., 2004; Maneesha et al., 2011; Sridevi et al., 2019; Jagadeesan et al., 2019).

Sixteen years long-term study of wang et al., 2021 and studies of Madhupradap et al., (1996), Jyothibabu et al., (2008), Jagadeesan et al., (2017) and Santhikrishnan et al., (2021) highlighted the consistency of upwelling induced high phytoplankton biomass in the coastal waters of Arabian sea. However, the upwelling was weak along the east coast of India and found as patches along the coast (Shetye et al., 1991). Thushara and Vinayachandran (2016) reported the prominent phytoplankton bloom between off Kakinada (hereafter KKD) and Visakhapatnam (hereafter VSKP) in the Western Bay of Bengal during the Southwest Monsoon period. Coastal upwelling and the advection of upwelled waters to the offshore was the reason for high Chlorophyll *a* (Chl *a*) concentration in coastal regions and their spatial extension towards the offshore (Rao et al., 1986; Johns et al., 1993; Thushara and Vinayachandran, 2016). Despite these facts, advected waters impact on column hydrography and their concomitant effect on biological production still need to be addressed in WBoB.

The coastal regions between Kakinada and Visakhapatnam is one of the major fishing zones in the Western BoB (Edward et al., 2019). The Godavari river is one of the major Indian rivers. The Godavari river originates near Nasik city in the Western Ghats, flows over a distance of 1480 km and drains into the Bay of Bengal. The annual rainfall of the Godavari river basin was 1512 mm y^{-1} , and 70% occurred during the SWM period (Sarma et al., 2009; Sarma et al., 2010). Annual mean discharge was 105 km³ in that major proportions happened from June to September, with a peak in August. Godavari river flows was regulated by Dowleiswaram (situated ~60 km upstream of the

mouth). After Dawalaiswaram dam, the river bifurcates into three distributaries. The eastward flowing major tributary is the Gautami-Godavari, with an average width of 1200m and 67% discharge occurring through this tributary. Vasistha-Godavari and Vainateyam are the other two southward flowing tributaries (Sarma et al., 2010). Godavari river discharge was $>5000 \text{ m}^3 \cdot \text{S}^{-1}$ to adjacent coastal regions (Sarma et al., 2010; Acharya et al., 2012) during the peak discharge period, which may inhibit the upwelling process in the coastal waters off Godavari. The Visakhapatnam is a port city located ~ 200 km north of the Godavari river estuary. The coastal regions of Visakhapatnam did not experience any direct influx from the major rivers. Minor rivers such as Gosthani and the Sarada-Varaha flow north of 15kms and south of 40kms from Visakhapatnam. While compared to Godavari, the influx of Gosthani and Sarada-Varaha into the coastal waters was negligible.

Eddies are ubiquitous in the BoB and significantly alter the hydrography of BoB (Dandapath and Chakraborty, 2016). A warm-core (Anticyclonic) eddy was reported in the off Kakinada during the southwest monsoon period. Anticyclonic eddies are predominant over cold-core eddies (CE) in BoB. Anticyclonic eddies are relatively larger, impoverishing nutrients in the euphotic layer and resulting the low production (Sarma et al., 2018). The information provided above indicates that the cross-shore sections of VSKP and KKD may have different water masses. An exhaustive study to capture the phytoplankton biomass change in spatially existing different water masses are meager in BoB.

The present study hypothesized that coastal upwelling is predominant in non-river influenced coastal locations (VSKP) in BoB. In contrast, the freshwater influx from the Godavari river suppresses the coastal upwelling in KKD. In addition, this study attempted to explain how the physico-chemical parameters and phytoplankton biomass of upwelling water advection paths differ from the river influx and anticyclonic eddy influenced cross-shore section of the KKD. Satellite data sets of Sea Surface Temperature (SST) and Chlorophyll-*a* were downloaded on a regular basis to identify coastal upwelling process associated bloom evaluation and their spatial spread in the central western BoB (Figure 1). Twenty points are sampled during the SWM in the present study to explain the following objectives Viz. a) to study the hydrographical parameters and Chl *a* differences between riverine influx influenced coastal situation and upwelling dominant coastal situation in WBoB; b) to assess the influence of upwelled water advection on the spatial and vertical distribution of hydrobiology and compare its distinctiveness with riverine influenced slope and warm-core eddy influenced offshore situations.

2.0 Materials and methods

2.1 Sampling and Methods

Samples were collected from 20 sampling points in the western central Bay of Bengal as a part of the onboard RV Sindhu Sankalp (SSK 130) cruise during the Second week of August 2019 (11 - 16 August 2019). Stations 1 - 10 were the cross-shore section of Visakhapatnam, and stations 11 - 20 were in the offshore to coastal regions of Kakinada (Figure 2). Stations are classified as coastal (1 -3; 19, 20), slope (4 and 5; 17-18) and offshore (7-16) based on the depth of the sampling points. Inshore, coastal and slope locations of the KKD transect are close to the barmouth of the Gautami-Godavari branch. Sea surface Height Anomalies (SSHA) and geostrophic currents (U and V), Sea surface temperature, Salinity and Chlorophyll *a* (daily mean and Monthly mean) were retrieved (more details about the satellite parameters were presented as table in Supplementary material 1) from the Copernicus Data sources (<http://marine.copernicus.eu>) and plotted as 2D colour maps using ODV software Version 4.7 (<http://odv.awi.de/>). The eddies are defined as cyclonic or anticyclonic based on rotation speed ($> 20\text{cm. s}^{-1}$) and direction (clockwise or anticlockwise) of the geostrophic currents and amplitude of the SSHA ($> 10\text{cm}$) (Vinayachandran, 2009; Chelton et al., 2011). PAR and Euphotic depth (8 days mean) for the study region were downloaded from <https://hermes.acri.fr/>, and values for each station were calculated from the closest pixels average of the sampling point. Eddies are defined as per The PAR at a specific depth was calculated using Gallegos (2001) formulae and the results were displayed as a vertical contour plot.

The vertical pattern of the salinity and temperature was measured through Rosette Sea-Bird CTD (Conductivity, Temperature, Depth profiler). Turbidity and Chlorophyll *a* was measured through the turbidity meter (WET Labs ECO-NTU - Turbidity meter) and Fluorometer (WET Labs ECO-AFL/FL), which one attached with CTD rosette. Mixed Layer Depth (MLD) was calculated as the depth where density equals the sea surface density plus an increment of density equal to 0.8°C . The Isothermal layer is defined as the depth at which the temperature is 0.8°C lower than SST (Kara et al., 2000; Thushara et al., 2019). The barrier exists between isothermal and MLD base (Vinayachandran et al., 2002; Rao and Sivakumar, 2003; Girishkumar et al., 2011; Thushara et al., 2019; George et al., 2019). Water samples from 5 - 8 discrete depth layers were collected using Niskin samplers to analyse the nutrients and Chlorophyll *a*. The sampling depth was decided based on the downcast profile of CTD. Samples from 2m (close to the surface), 5m, 10m, 20m or 25m were collected uniformly at all stations. Three or four samples were collected between 30-60m depth layer (except inshore locations) to cover the different layers of subsurface Chlorophyll *a* maxima and hydrography. Two or three samples were also collected between 70 - 100m representing deep layers.

Surface water samples were collected using the pre-cleaned sampling bucket. Dissolved oxygen was measured through Winkler's method and the CTD dissolved oxygen data were calibrated with the measured data to obtain a high-resolution vertical profile. Nutrients were analyzed onboard using advanced instruments SYSTEA μ MAC 1000 and Green Eyes EcoLAB following the standard procedure of Grasshoff et al., 1983.

2.2 Chlorophyll-*a*

One to two litre of water samples were filtered through the 0.2 μ m filter paper using the mild vacuum, wrapped in aluminium foil and stored in liquid nitrogen until the sample analysis. In the laboratory, Chlorophyll *a* was extracted with 90% acetone in overnight dark incubation at 4°C and measured using a calibrated Turner Fluorometer (Turner Model No: UNESCO, 1994). CTD Chlorophyll *a* was corrected with the lab measured Chl *a* for high resolution data set using the regression equation line. Regression analysis was performed in the XL stat Pro software. Separate regression equations were for the coastal conditions (Corrected Chl *a* = CTD Chl *a* *1.18 + 1.365; $r=0.92$; $N=30$; $P<0.01$), slope and offshore situations (Corrected Chl *a* = CTD Chl *a* *0.90 + 0.438; $r=0.89$; $N= 90$; $P<0.01$) to avoid the interference of the turbidity (Supplementary material 2). The column-integrated chlorophyll *a* concentration was calculated using the formula of Dyson et al. (1965). For column integration of Chl *a* concentration, surface – 25m was used in inshore regions; upper 100m was used in other regions.

2.3. Univariate and Multivariate analysis

Univariate analysis was performed to compare the spatial differences of the hydrography within and between the transects. Multivariate ordination technique was used to explain the interrelationships between physico chemical parameters and Chl *a* distribution. DCA (Detrended correspondence analysis) was performed to find the suitable ordination method for the present data sets. Results of the DCA (axis gradient length <2) suggested that RDA (Redundancy Analysis) is the best ordination method for the present study (Birks, 1998; Leps and Smilauer, 2003). The data sets of Chl *a* and integrated Chl *a* were log transformed and centered prior to the analysis. Two sets of RDA (upper layer and entire water column) were performed to understand the relationships between various physical processes associated hydrographical settings and Chlorophyll *a* distribution. RDA analysis is performed by the standard procedure of Leps and Smilauer (2003) using CANOCA version 4.5. RDA ordination significances were tested with the Monte Carlo permutation test.

3.0 Results

3.1 Sea surface temperature, Sea surface Height Anomaly and Salinity

SST begins colder during the first week of June in some places along the east coast of India, representing coastal upwelling and its found as patches along the east coast. Temperature and salinity gradients between coastal locations VSKP and the surroundings represented a prominent upwelling (relatively cool and high saline condition) during the second week of July (Figure 3). The spatial extent of this upwelled coastal waters advection was found from coastal to offshore over time. During the last week of July, upwelled coastal water extends over 250 km from the coast with a width of 20-60 km. The spatial spreading of upwelled waters was noticed during our sampling period also.

SSHA and geostrophic current pattern visualized, East India Coastal Current (EICC) was unorganized and several eddies along the western Bay of Bengal during the Southwest Monsoon period (Figure 3). A prominent anticyclonic was present in off Kakinada (southern side of the VSKP) and a cyclonic eddy was present on the northern side of the VSKP (Figure 3). Advection path of upwelled coastal water was in the interface region between periphery of cold core and warm core eddy. The EICC flow is southward in the Northwestern Bay of Bengal, carrying the low saline waters from the north. Southward advection of low saline waters deviated towards the offshore by cold core eddy periphery at $\sim 18^{\circ}\text{N}$ (Figures 3 and 4). The western periphery of anticyclonic eddy is very close to the coast at $\sim 16^{\circ}\text{N}$ and flows along the coast and deflected towards the offshore around 18°N . According to the SSHA patterns, the VSKP transect was in non-eddy condition or an interface region between warm and cold core eddy. Offshore locations of KKD was inside the eddy, shelf and slope locations were in the eddy periphery, coastal location was outside of the eddy.

Low saline plume was found close to the Godavari and Krishna river mouths, with a spatial extent of 30-40 km. The spatial distribution of salinity and temperature showed the existence of prominent upwelling between the Srikakulam and Kakinada. The spatial extent of the upwelling zone was found between the boundaries of low saline advection from the north and freshwater flow from the Godavari River. Low saline water of Godavari is advected as a thin band ($\sim 30\text{km}$ width) to the north (towards off Visakhapatnam) by the outer periphery of the warm core eddy and the advection path was ~ 100 km away from the coast.

3.2 Upper layer distribution of salinity, temperature, dissolved oxygen and turbidity

Godavari River influenced the upper layers of inshore, coastal and slope locations of KKD. Upper layer salinity increased towards the offshore in KKD (Figure 5). In contrast, inshore was

relatively cooler and had high salinity than offshore in VSKP. The vertical influence of the freshwater influx was found in a thin layer in slopes. Upper layer differences in salinity and temperature between VSKP and KKD were significant in coastal waters. Relatively high salinity (0.41 – 2.4; Av. 1.55) and less temperature (0.78 - 2.79°C; Av. 1.6°C) in coastal waters of VSKP indicates upwelling was more prominent in VSKP than KKD (Table 1). In slope regions, upper layer was relatively cool (~1°C) and high saline (1.1 units) with high nutrients (detailed in the below section) in VSKP compared to KKD, representing the advection of the upwelled coastal waters (Table 1 and 2).

Low salinity was found in the upper layer of locations 8 and 9 in VSKP transect, which could be due to adjoining warm-core eddy periphery advected low saline waters from the Kakinada. This is the first observation evidencing northward transport of Godavari waters by the warm core eddy, influencing the salinity of the VSKP offshore waters (Figures 4 and 5). Dissolved oxygen was spatially high in the coastal waters of KKD compared to the VSKP, but the differences were comparable between VSKP and KKD. In offshore regions, upper layer dissolved oxygen was higher in VSKP than KKD. Turbidity was relatively high in the riverine water influenced locations. Turbidity was 1.19 ± 0.13 NTU in the coastal locations of VSKP, but this was 1.45 ± 0.22 NTU in KKD. Low saline water influenced offshore location turbidity was comparatively higher than in adjacent locations (Figure 6 and Table 1). Upper layer PAR was $\sim 600 \mu\text{mol m}^{-2} \text{s}^{-1}$ (downloaded data set) in the study area. Euphotic depth was shallower in coastal locations and increased offshore. In coastal and slope regions, euphotic depth was associated with upper layer turbidity and found relatively high attenuation and shallow photic layer in riverine influx influenced KKD compared to VSKP (Figure 6).

Satellite-derived parameters and hydrographical observations together explained the existence of spatially different water masses within and between transects of VSKP and KKD in upper layers. Based on the hydrographical parameters, sampling locations can be assembled into different zones. Coastal locations of VSKP (locations 1-3) can be termed as the upwelling coastal conditions (non-river influenced). The advection of the upwelled water is traceable to locations 4 – 6, representing the upwelled water advection influenced conditions. Location 8-9 represents the northward advection of low saline advection influenced offshore location. Location 7 was the transition region between the upwelled water and low saline water influencing location. Location 10 was away from the advection of water masses. Coastal (locations 19 and 20) and slope locations (locations 17 and 18) of KKD denote the river influenced conditions; locations 11-13 and 14-16 represent the core and periphery of warm-core eddy influenced conditions (Table 1).

3.3 Vertical pattern of the salinity and temperature

The vertical pattern of hydrographical parameters showed significant differences within and between cross-shore sections of VSKP and KKD (Figures 4-6). Temperature 25 °C (T25) and Isohaline layer of salinity 34 (SAL 34) were near the surface in the inshore locations of VSKP but were pushed down below 10m in the KKD by freshwater. The T25 layer is relatively deeper in KKD (95-130m) compared to VSKP (57 - 90m) due to warm core eddy (Figure 5). The SAL34 layer was relatively shallow (42 - 65m) in VSKP than KKD (74 - 98m). A thin layer of warm core eddy advected low saline water influence was found in the VSKP offshore location. In coastal locations, hypoxic layer (2 ml.L⁻¹) was deeper in KKD than VSKP. Hypoxic layer was ~40m in the slope locations of VSKP and KKD (Figure 5). In offshore locations, hypoxic layer was relatively deeper (below 100m) in warm core eddy locations, followed by the eddy periphery (60 - 80m) and shallower in non-eddy locations (43 - 85m). At a 100m depth layer, warm core eddy locations were warmer (3 - 8°C), less saline (0.5 - 0.8) and relatively oxygenated (1.5 to 3 times) compared to non-eddy.

3.4 Variability in the isothermal, mixed and barrier layers

Salinity stratification was high in the low saline influenced upper layers. Isothermal layer was shallow in the inshore location and deepened towards the slope and offshore regions (except 7). Locations proximity to riverine input, ML was shallowest (<10m) in coastal and slope locations of the KKD transect. In cross-shore section of VSKP, ML was relatively deeper (48m) in location 10 compared to upwelled water advection (22 m) or low saline advection influenced (12m) offshore locations. ML was deepest in core of warm core eddy compared to other locations. BL was strong in a river influenced coastal locations and slope regions of KKD (5 - 15m in coastal locations; 32 - 36m in slope) compared to VSKP (4-9m in coastal locations; slope: 11 - 17m). In offshore locations, barrier layer thickness was strong (47 - 54m) in low saline influenced offshore location of VSKP (Location 8 and 9) compared to other offshore locations (Figure 5).

3.5 Distribution of Nutrients

In coastal locations, nitrate and phosphate concentrations were relatively high in VSKP, while silicate concentration was high in KKD. In river influenced slope region, nitrate and phosphate concentration was less compared to upwelled coastal waters advection influenced slope (Table 2). Nitrocline was extended from surface to base of the thermocline in KKD, but this was different in upwelled coastal water advection and low saline advection influenced offshore locations of VSKP (Figure 7). The upper layer had high nutrients, separated from subsurface high nutrients layer by an

intermediate low nutrient layer. The vertical pattern of the nutrients shows that upwelled water advection altered the nutrients in their path and found their influence is vertical extended ~ 25m from surface.

3.6 Chlorophyll *a* distribution

Chlorophyll *a* in the upper layer was varied from 0.12 to 11.4 mg.m⁻³. The riverine influx and upwelling coastal locations had > 2 mg.m⁻³ of Chl *a*. However, exceptionally high Chl *a* concentration found in the upwelling influenced inshore and coastal locations (Figure 8 and Table 3). Upwelled water advection enhance the upper layer Chl *a* concentration in shelf and slope regions of VSKP and riverine flux enhanced the Chl *a* concentration in KKD. Upper layer chlorophyll *a* was relatively high in the slope locations compared to coastal locations in KKD. The vertical expansion of the high Chl *a* layer (>1 mg.m⁻³) was relatively deep in upwelled coastal waters and their advection path but this was found as a thin layer in the KKD due to stratification and thick BL (Figure 8). In the offshore locations, upper layer Chl *a* was several folds higher in VSKP than KKD.

Subsurface Chl *a* maxima (SSCM) feature was prominent in the slope of VSKP, but it was absent inshore and coastal locations of VSKP and KKD. It was either absent or less prominent in riverine influenced slope regions of KKD but exhibited a different pattern in VSKP (Figure 8). In locations 4 and 5 (slope regions of VSKP), upper high Chl *a* and SSCM high Chl *a* layer was separated by an intermittent low Chlorophyll *a* layer. In location 6, high Chl *a* layer vertically extended from the upper layers to base of thermocline. In location 7, upper high Chl *a* layer found at intermittent depths of 15-25 m (Figure 8) and it was well separated from the SSCM (which existed at a depth of 50m) by an intermittent low Chl *a* layer. The SSCM layer was 57m and 62m in locations 8 and 9. Noticeably, SSCM layer Chl *a* was 2-3 folds high in slope regions compared to offshore regions of VSKP. In the KKD transect, SCM was absent and found SSCM at a depth of 85-95m in the inside eddy locations, slopping towards the periphery (45-67m). Chlorophyll *a* biomass in the SSCM layer was less in warm core eddy locations.

3.7 Vertical structure of the Chlorophyll *a* pattern

The present study recognized four Chlorophyll distribution patterns (Figure 9). They are Surface Chlorophyll maxima (SCM), Subsurface Chlorophyll Maxima (SSCM), Double Chlorophyll Maxima (DoCM) and Extended Chlorophyll Maxima (ECM). The presence of the SCM or SSCM in the Bay of Bengal is well documented; however, the pattern of DoCM is relatively new and ECM is a new pattern observed in BoB. Inshore and coastal locations of the VSKP and river influenced coastal locations of KKD have a prominent SCM, while SSCM was absent or not prominent. The

offshore regions of KKD (including location 10) have less Chlorophyll in the upper layer and found the SSCM in relatively deeper depths. The DoCM pattern was identified in the coastal waters advection influenced slope, offshore regions and low saline advection influenced offshore locations of the VSKP. Both SCM and SSCM layers were present in DoCM and well separated by an intermittent low Chlorophyll *a* layer (Figure 9). Two different DoCM patterns were observed in the present study. In type I, first high Chl *a* layer is in the upper layer and a second in the subsurface layers. In type II, the upper layer had less Chlorophyll *a*, first high Chl *a* layer was in beneath the top layers (Below 15m) and a second-high Chl *a* layer was in further deep. Type I DOCM was found in the upwelled coastal waters advection influenced slope locations (4 and 5) of VSKP and type II was found in location 7. In location 6, high Chl *a* condition (>1) extended from the surface to 40m; this was defined as Extended Chlorophyll Maxima (Figure 9). ECM structure was formed due to adjoining the lower boundary of the upper high Chl *a* layer and upper boundary of the SSCM layer.

3.8 Integrated Chlorophyll *a* concentration

Integrated Chlorophyll-*a* concentration in the inshore waters was relatively higher in VSKP than KKD (Figure 10). Integrated Chl *a* concentration was $116.31 \pm 13.78 \text{ mg.m}^{-2}$ in the VSKP slope and $89.85 \pm 19.15 \text{ mg.m}^{-2}$ in the KKD. Among the total Integrated Chl *a* concentration, 43 - 58% accumulated in the upper 10m in the KKD, but it vertically disseminated in different layers in VSKP (Figures 10 and 11). In location 6, integrated Chl *a* concentration was 111 mg.m^{-2} in that share by the upper 50m almost equal, indicating no clear separation of SSCM layer from the upper layer Chl *a*. In location 7, integrated Chl *a* concentration was 66.09 mg.m^{-2} in that upper 10m layer contributed only 3%, but the subsurface Chl *a* maxima layer contributed 25%. Integrated Chl *a* concentration in offshore location was significantly higher in the low saline advection influenced locations of VSKP than the KKD. In locations 8 and 9, upper layer (0-10m) contributed $>50\%$ in the column integrated Chl *a* concentration, but this was only $<5\%$ in the adjacent offshore (location 10) and warm core eddy. Deep layers (70-100m depth layers) contribution in the total integrated Chl *a* was significant in the core eddy and eddy periphery (Figure 11).

3.9 Interrelationships of the hydrographical parameters and Chlorophyll *a* distribution

RDA triplots explained the interrelationships of hydrographical parameters and Chlorophyll *a* distribution. Hydrographical parameters explained 80% of Chl *a* distribution in the upper layers. RDA triplot visualized the hydrographical parameters and Chlorophyll *a* distribution differed within and between transects. Warm core-eddy locations were in the left-hand side of the plot along with temperature and opposite direction to the nutrients and Chlorophyll *a* axes, indicating nutrients poor

warm water with less Chl *a* in the warm core eddy. Whereas inshore and coastal locations of VSKP and KKD were oriented in the upper portions of right hand side with close orientation with nutrients representing the upwelling and river runoff enhances the upper layer nutrients results in the high Chl *a* (Figure 12). Temperature overlaid attribution plot shows that VSKP coastal locations were assembled in the extreme corner of the reducing gradients of the temperature and increasing gradients of the nutrients represent the intense upwelling. Upwelling advection influenced the slope and offshore location of VSKP, riverine influenced slope locations of KKD had moderate levels of nutrients and oriented with the down portions of the RDA plot. Chlorophyll *a* attribution plots show that the upper layer chlorophyll *a* was relatively high in the VSKP coastal locations compared to KKD (Figure 12).

RDA triplot, Figure 13 visualized their column differences of the physicochemical and Chl *a* distribution differences within and between the sampling locations. Riverine influx influenced coastal and slope location was oriented upper right hand side of the plot with a close association with turbidity and positive orientation with the nutrients. Upwelling advection influenced and low saline water influenced locations were oriented in lower portions of the right hand side of the plot with the increasing axis of the nutrients and relatively high salinity. Warm core eddy influenced offshore locations were oriented left hand side of the plot with the increasing gradients of the subsurface layer of dissolved oxygen, temperature and opposite to the nutrients axis represents that warm, less nutrients and relatively oxygen rich waters sinking deep in warm core locations. Chl *a* distribution differed with the prevailing water masses. Chl *a* axis of 30m and 40m were found in close to the locations of the 4 - 6 with the positive orientation with the nutrients, indicating the existence of prominent subsurface Chl *a*. River influenced location upper layer Chl *a* was high, but the vertical extend of riverine flux was thin. The overall pattern of the subsurface RDA represents that upwelling influenced slope and offshore locations had high Chlorophyll *a* in the upper and subsurface layer (30 and 40m). However, riverine influenced slope locations had high chlorophyll *a* in the upper layer, but subsurface layer Chlorophyll *a* was less prominent. The subsurface chlorophyll *a* pattern in coastal and slope locations in the KKD was influenced by the riverine influx related stratification and turbidity. Warm core location, deep layer Chlorophyll *a* concentration was relatively high.

4.0 Discussion

The upwelling (Cool and high saline) was found as patches along the east coast of India during the Southwest monsoon period (Shetye et al., 1991). The Upwelling along the Visakhapatnam generally occurs from Feb – August with two intense spells, March - April and July – August (Rao et al., 1986; Rao et al., 1995; Vijayakumaran et al. 1996; Vijayakumaran, 2004; Vijayakumaran, 2005;

Rani et al., 2018). However, commencement, strength and duration exhibits inter-annual variations. Upwelling signals were initially close to the coast and advected offshore (Murty and Varadachari 1968; Vijayakumaran et al., 1996). This was evident in the close observation of the temperature differences ($> 1^{\circ}\text{C}$) between the advection path of upwelled water and their surroundings. This similar kinds of the difference in the temperature frontal areas and their surrounding was reported by wang et al., 2020 while using the high resolution satellite data sets. The numerical modeling and observation study of Vijayakumaran, (2004) pointed out that rival upwelling phases occurred during July and August after a subsidence of the first upwelling phase in May. Prominent upwelling in inshore locations of VSKP was reported during the second week of July, which was in agreement with the previous studies (Vijayakumaran et al. 2004; Rao et al., 2005). Upwelled inshore locations were cool and had high saline compared to adjacent offshore in the VSKP transect (Figure 5 and Table 1). Vijayakumaran et al. (1996) and Muralidharan et al., (2007) also reported similar temperature and salinity gradients between the upwelled coastal waters and offshore in the BoB.

The EICC is not prominent along the east coast of India during the southwest monsoon period (Shankar et al., 2002; Jagadeesan et al., 2021), though its flow direction is southward in the northwestern BoB (Figure 3). EICC and cold core eddy collectively advect the low saline plume waters from north to south and it gets deflected offshore at near 18°N (Chaitanya et al., 2014; Jagadeesan et al., 2021). Discharge from the Hooghly and Mahanadi and their southwards advection inhibits upwelling as far as 18°N (Shetye et al., 1991; John et al., 1993; Shetye et al., 1993). Johns et al., 1993; Mahapatra and Rao, 2017). Godavari and Krishna river influx suppresses the upwelling in their adjacent coastal waters. Intense upwelling was found in an intermittent region (Srikakulam and north of Kakinada) between low saline advection from the north and Godavari river influx (Figure 4). This was consistent with the observation of high saline and cool waters between Gopalpur and Kakinada reported during the southwest monsoon season by Mahapatra and Rao, 2017.

Upwelling signatures were evident up to surface layers in Visakhapatnam; however, this was below 10m due to the capping of low saline waters in coastal locations KKD (Figure 5). This kind of inhibition of upwelling by the low saline cap associated with the river input along the east and west coasts of India reported by John et al. (1993); Gupta et al. (2016); Anjusha et al., (2018); Santhikrishnan et al., (2021). River influenced coastal locations (coastal locations of KKD) were relatively warmer and less saline compared to upwelled situation (coastal locations of VSKP). The suppression of upwelling intensity by the riverine influx depends upon the magnitude of the riverine flux, flow direction of the low saline waters, coastal morphology etc. A relatively shallow mixed layer and strong barrier layer were found in the river influenced locations, this was in accordance

with the observations of Vinayachandran et al., (2002); Thushara et al., (2019). High-suspended particle load in riverine inputs (Bharathi et al., 2018) results the high turbidity in the coastal waters of KKD compared to VSKP.

The hydrography of the western BoB is influenced by various physical processes such as eddies, coastal currents, Rossby wavers etc., (Sarma et al., 2013; Amol et al., 2019; Bharathi et al., 2018; Jagadeesan et al., 2021). Eddy cores can transport the water masses (Contie and contie, 2016; Huang et al., 2010; Heywood and Priddle, 1987; Jagadeesan et al., 2021) over a distance of ~ 500km from the eastern BoB towards the western BoB. In addition to core-eddy, eddy peripheries can also transport adjoining water masses in their route (Xu et al., 2019) and advected water mass hydrobiology is different from the surroundings. Southward advection of low saline plume advection from the northwestern Bay of Bengal by EICC was reported by several researchers (Shetye et al., 1991; Chaitanya et al., 2014; Gopalakrishna et al., 2002 and Jagadeesan et al., 2021). However, the present study evidence warm core eddy periphery advecting adjoining low saline (Godavari coastal) waters towards the north over a distance of ~ 250 km and the advection path was away from the coast (Figure 4). Northwardly advected low saline coastal water was spotted ~100km away from the shore in off Visakhapatnam (intermittent low salinity in cross-shore section). Satellite and *insitu* observations visualized the offshore advection of upwelled coastal waters (Figures 2 to 4). The advection path was in the interface regions between warm and cold core eddies (Thushara and Vinayachandran, 2016). The low saline advection from the north and south and the intensity of upwelling controlled the course and shape of the upwelled water advection path. Due to riverine influx from the Godavari rivers, offshore advection of upwelled water and warm core eddy situation prevailed water masses were differed within and between cross-shore sections of VSKP and KKD. The existence of different water masses in the cross-shore section of the Bay of Bengal related to local riverine inputs and advection of the water masses from the north was reported by Bharathi et al., 2018, Amol et al., 2019; Jagadeesan et al., 2021, this was in accordance with the present study.

In the present study, both the coastal locations had $>2\mu\text{M}$ of nitrate, indicating that the Godavari riverine inputs and upwelling boosted the nutrient concentrations in the coastal locations. However, the magnitude was higher in the upwelling conditions than in riverine influx. The reported nitrate values in the coastal locations of KKD were relatively high compared to northern regions, which was consistent with the studies of Sarma et al., (2012 and 2013) and Bharathi et al., 2018, both which explained the importance of perennial riverine runoff in nutrient distribution in the southwestern Bay of Bengal. Upwelling processes bring significant nutrients to surface layers in coastal locations of VSKP. However, salinity stratification associated with runoff inhibits the upward

movement of the nutrients. This was in accordance with the observations of Vijayakumaran et al. 2004; Gupta et al., 2016; Sarma et al., 2018; Anjusha et al., 2018. In addition to the inorganic nutrients, Godavari river dumps a significant load of organic nutrients into coastal waters during the peak discharge period (Prasad, 2014). This riverine organic nutrient can be an additional nitrogen source for phytoplankton production in the BoB (Antia et al., 1991; Moschonas et al., 2017; Sarma et al., 2019).

The vertical distribution of the hydro-biological parameters is altered by upwelled water advection and runoff from the Godavari river. Vertical extension of the upwelled water advection influence was noticed up to 25m, whereas the river influence was found as the thin layer (Figure 5). Upwelling processes upsloped the nutrients rich, cool and less oxygenated waters into upper layers (Sarma et al., 2018; Jagadeesan et al., 2019) was evident in the coastal location of VSKP. Warm-core eddy down slopes the oligotrophic conditions to deeper layers (Sarma et al., 2018; Prasannakumar et al., 2002; Parasannakumar et al., 2004; Jyothibabu et al., 2021) and found T25, Sal 34 layer was in relatively deep in KKD offshore compared to VSKP. This indicates that relatively warm, low saline, nutrients poor and oxygenated waters of the upper layers were sinking to the deeper depths in the warm core eddy (offshore of KKD). Upwelled water advection enhances the upper layer nutrients up to 20-30m and this was separated from the subsurface high nutrient layer by an intermittent low nutrient layer (Figure 7), which could be related to barrier layer formation in BoB (Vinayachandran et al., 2002; Thushara et al., 2019).

Phytoplankton biomass was $>2 \text{ mg.m}^{-3}$ in the coastal locations of VSKP and KKD (Figure 8), representing that both upwelling and the riverine input enhanced the Chlorophyll *a*, but it was exceptionally high in VSKP (11.4 mg.m^{-3}). This results were in agreement with the studies of Madhupradap et al., (1996); Jyothibabu et al., 2008; Jagadeesan et al., (2017) and Wang et al., (2021), which one highlighted significance of the upwelling in the enhancement of the Chl *a*. In KKD, upper layer Chl *a* was higher in slope than coastal locations. The presence of the *Noctiluca* swarm (red) in the coastal waters of Kakinada was a noteworthy feature during the present study (Supplementary material 3). *Noctiluca* is the major grazer of phytoplankton (Busky, 1995; Elbrachter and Qi, 1998; Nakamura, 1998; Arunpandi et al., 2017), and their grazing pressure on phytoplankton was high compared to copepods (Arunpandi et al., 2017). Therefore, the grazing pressure of *Noctiluca* on the phytoplankton stock may be the reason for relatively less chlorophyll *a* in the coastal regions of KKD compared to slope regions.

Upwelled water advection path has high Chl *a* concentration compared to adjacent regions. The spatial extension of the high chlorophyll *a* layer depends upon wind mixing (Amol et al., 2019),

nutrients availability (Sarma et al., 2018; Jagadeesan et al., 2021) and nutrients assimilation by phytoplankton (Sarma et al., 2013). Subsurface Chlorophyll *a* Maxima (SSCM) was prominent in the slope regions of the VSKP, but this was absent or had less Chl *a* in the slope regions of KKD. PAR in the prominent SSCM layer was found to be 5 - 20 $\mu\text{mol m}^{-2} \text{s}^{-1}$ in the present study (Figure - 14) which was consistent with the findings of Geider et al., (1985); Wetz et al., (2003); Jyothibabu et al., (2018). Relatively high turbidity with salinity stratification was reported in riverine influenced slope locations of KKD. Underwater PAR penetration is inversely related to the upper layer turbidity. The PAR availability in the stratified layer is a deciding factor of planktonic productivity. Turbidity shallows the optimum light layer for phytoplankton production and stratification associated thick barrier layer inhibits the upward movement of nutrient rich waters (Vinayachandran et al., 2002; Thushara et al., 2019), resulting in a mismatch in optimum light for production and subsurface nutrients layer. This mismatch resulted in less Chl *a* (Jyothibabu et al., 2018; Sarma et al., 2018; Jagadeesan et al., 2021) in SSCM or absence of SSCM in river influenced slope regions. In warm core eddy offshore, SSCM maxima were deep and had less Chl *a* concentration than non-eddy offshore regions. Warm core eddy down sloped the oligotrophic upper layer to deeper depths and the high nutrients layer was below 60-80m, where the PAR was not optimum for high production, leading to less concentration in the SSCM. A similar mismatch of optimal light and nutrients layer in warm core eddy regions has been reported earlier in the BoB (Jyothibabu et al., 2018).

We identified four different types of Chlorophyll *a* distribution in this study, including one less known (DoCM) and one new pattern (ECM). DoCM is reported by Amol et al., (2019) and Jagadeesan et al., (2021) in low saline plume advection influenced slope and offshore regions of WBoB. In the present study, DoCM pattern is observed in the advection path of the upwelled water influenced slope and offshore regions and the southward advection of low saline waters influenced locations of Visakhapatnam. However, the DoCM pattern was absent in KKD slope regions, which one facing the freshwater influx from the Godavari River. Though the present study and Northwestern Bay of Bengal (study location of Jagadeesan et al., 2021) both faced the low saline water advection, SSCM was absent in the KKD; this would be due to turbidity differences between the study locations. Suspended load inputs to coastal waters by the southern peninsular rivers were high compared to northern glacial rivers (Sarma et al. 2012, 2013) owing to high turbidity in coastal locations (Wagh, 2016). Turbidity in coastal locations of KKD was 1.48- 1.6 NTU, which was ~50% higher than the study of Jagadeesan et al., 2021. High turbidity might be a reason for the absence of the SSCM in KKD slopes. The reported incidences of DoCM indicate that any physical processes or freshwater runoff increase the upper layer nutrients in slope and offshore regions without

significantly reducing light penetration is advantageous for DoCM formation. However, future research is needed to learn more about DoCM formation and the factors that cause it in BoB.

In this study, Extended Chlorophyll Maxima was reported in location 6. ECM is composed of two high Chl *a* cores, at depths of 10-20m and 25-30m (Figures 8 and 9). This indicates that a high chlorophyll *a* layer of upwelled water (relatively high dense) sub-ducted beneath the upper layers towards the offshore. ECM pattern upper boundary of SSCM and lower boundary of the SCM were joined without separation. In this study, two types of DoCM were identified: type I - SCM begins at the surface upper layer and SSCM at a depth of 30-60 m (locations 4 and 5); In type II DoCM (location 7), first maxima were at ~ 15 - 25m and a second one in at 45 - 50m (Figure 9). Upper high Chl *a* layer in location 7 was paralleled to the depth of the high Chl *a* core of location 6, representing the sub-ducted high Chl *a* extends spatially. However, this was not found in locations 8 and 9 due to their position away from the advection path. The present study could explain hydrobiology signatures of upwelled water advection path. However, for studying the fate of high Chlorophyll *a* layer towards the offshore in the advection path necessitated an extensive study along its trajectory.

5. Summary and conclusion

This study addresses the details of the summer phytoplankton bloom and its triggers in the cross shore sections off Visakhapatnam and Kakinada in WBOB. The hydrographic observations from two transects showed the presence of intense coastal upwelling in the VSKP with high Chl *a* biomass that advected towards the slope and offshore regions. However, the adjacent KKD transect was dominantly influenced by the freshwater input from the Godavari River, where the Chl *a* biomass was relatively low and limited to the surface layers. The contrast in the response of biological productivity is associated with existence of distinct water masses within and between these adjacent transects. Coastal upwelling enhances the availability of nutrients and results in high phytoplankton biomass in the VSKP. The advection of upwelled waters towards the slope and offshore region results in high phytoplankton biomass in their path. However, freshwater discharge from the Godavari River causes the low saline upper layers in coastal and slope regions of the KKD. Low saline upper layer capping the upward movement of the subsurface waters in KKD transects. Both riverine influx and upwelling enhance the phytoplankton biomass. However, the Chlorophyll *a* concentration was very high in the upwelling-influenced VSKP (8.52 ± 2.86 mg.m⁻³) transect compared to the river-influenced KKD (4.37 ± 2.04 mg.m⁻³) transect. Column integrated Chl *a* concentration was 2-3 folds higher in the slope and offshore regions of VSKP due to the presence of subsurface Chl *a* Maxima (SSCM). While it was absent in KKD, this disparity was due to turbidity associated light attenuation and stratification associated barrier layer formation in KKD. Sinking of

warm, less nutrient and relatively high oxygen waters was found in the warm core eddy influenced offshore locations of KKD.

A significant contribution of the present study is the identification of distinct patterns in the distribution of Chlorophyll *a* in WBoB associated with the prevailing different water masses. These include Surface Chl *a* Maxima (SCM), Subsurface Chl *a* Maxima (SSCM), Double Chl *a* Maxima (DoCM) and an Extended Chl *a* Maxima (ECM). Whereas SCM and SSCM are well-the known features of the BoB, others such as DoCM and ECM, are new features and could be quite significant in view of their contribution in the marine food web. Hence, this study is the first to delineate the influence of upwelling and river runoff in phytoplankton blooms in the coastal locations of WBoB.

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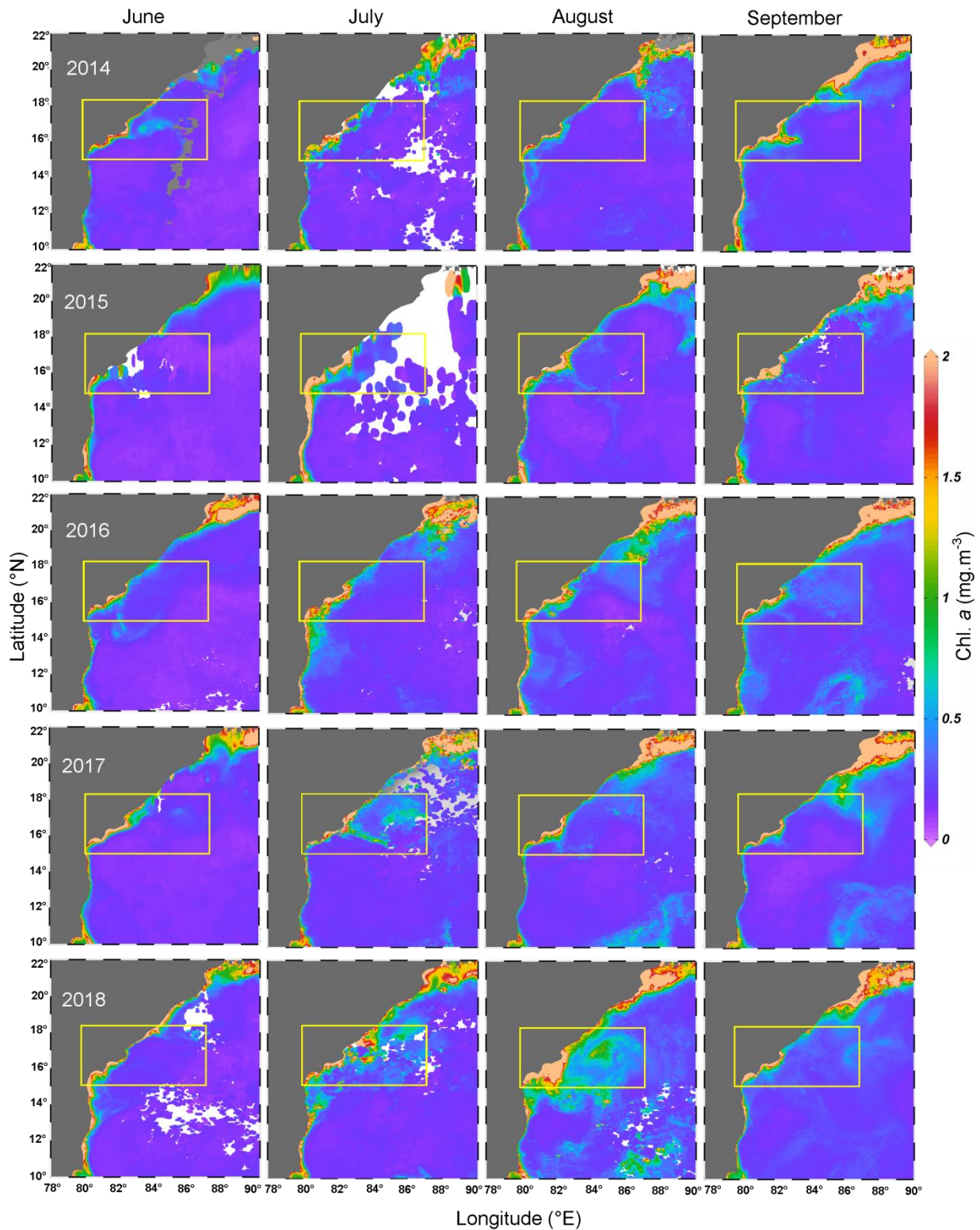


Figure – 1 Satellite imaginaries showing the distribution of Chlorophyll *a* (Monthly average) during the Southwest Monsoon (2014 - 2018). Irrespective of the year, prominent phytoplankton bloom (high Chl *a*) hot spot was found between 15 °N and 18° N (Yellow box) with horizontal advection from coast to offshore.

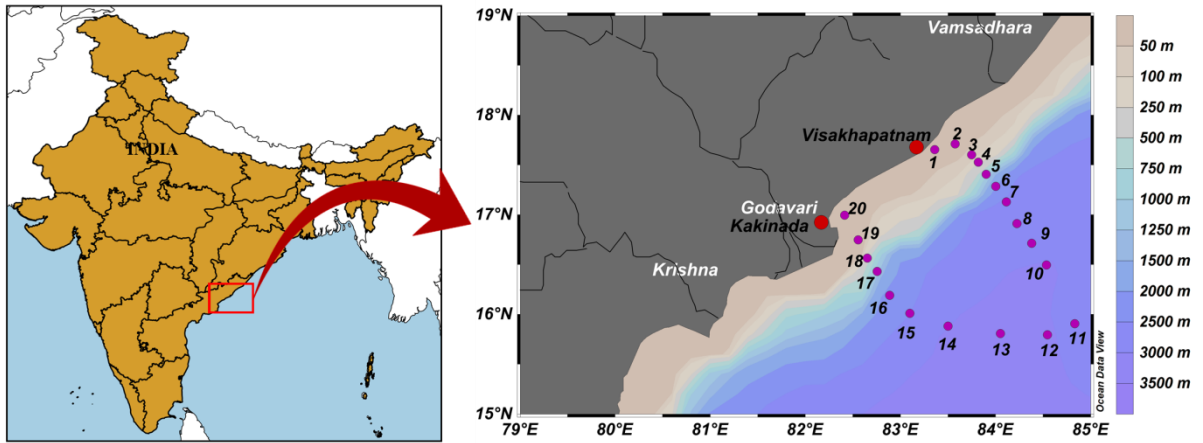


Figure – 2. Study area in the western Bay of Bengal (red box) with stations (pink dots). Totally 20 stations (pink dots) were sampled. Locations 1-10 were in the cross-shore section of the Off Visakhapatnam and locations 20-11 that in Kakinada. Major Rivers are labeled in white letters and the cities positions Visakhapatnam and Kakinada were marked by Red dots. Colour contours represents the bathymetry.

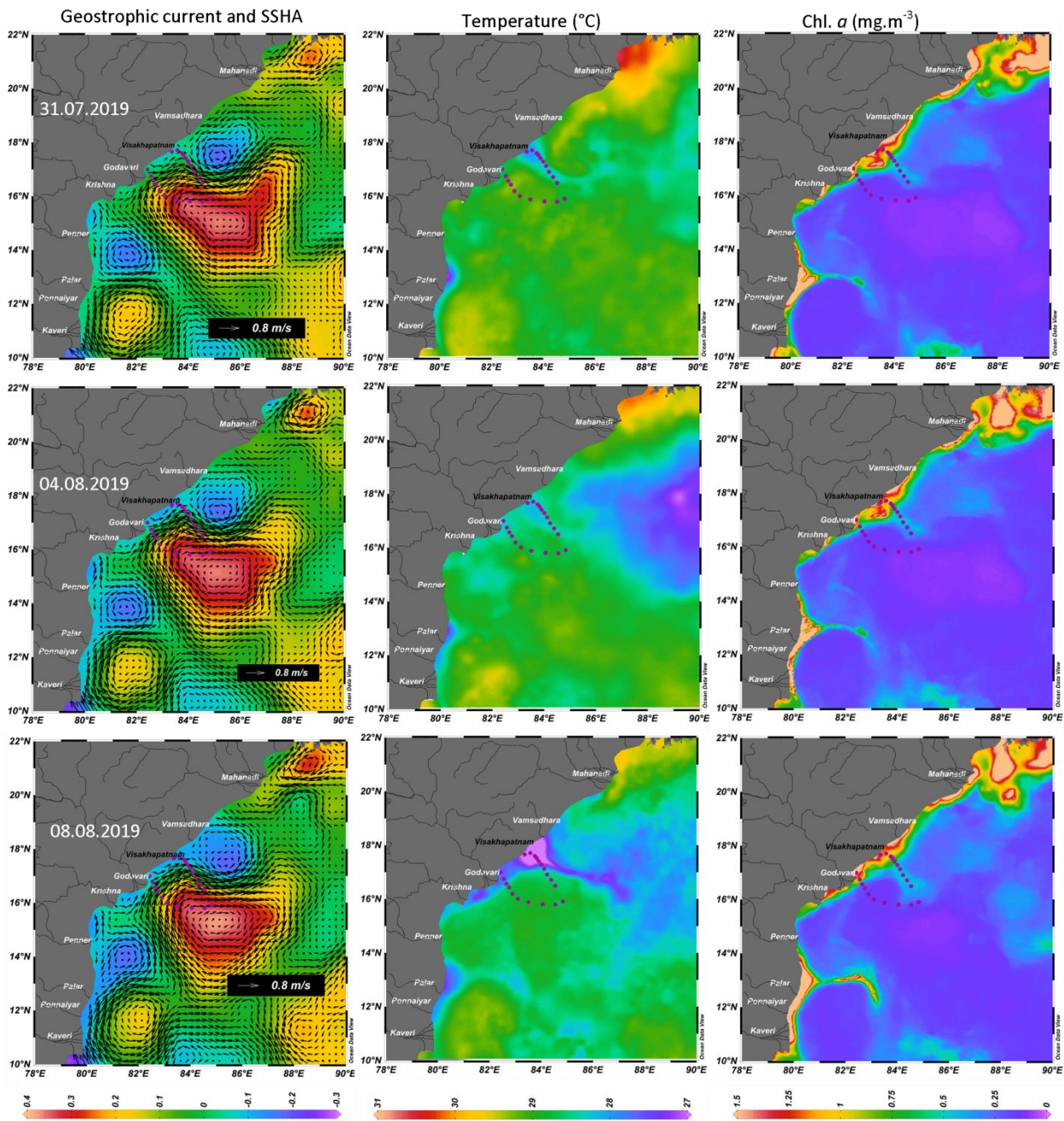


Figure 3 - Hydrography in the western Bay of Bengal from last week of July to first week of August 2019 (a week prior to our sampling period) represented by Sea surface temperature, Chlorophyll *a* and Sea surface Height Anomalies (SSHA) with geostrophic currents. Red dots are the sampling locations. Sea surface temperature shows the upwelling signatures (cool temperature) in some stretches along the east coast of India. Upwelling was more prominent in Visakhapatnam coastal regions and upwelled waters advected from coast to the offshore region. Advection path of the upwelled coastal was in a transition zone between the cold and warm core eddy. Cross-shore section of Visakhapatnam was in the path of upwelled water advection and adjacent locations. Kakinada offshore locations were in the core and inner periphery of the warm core eddy.

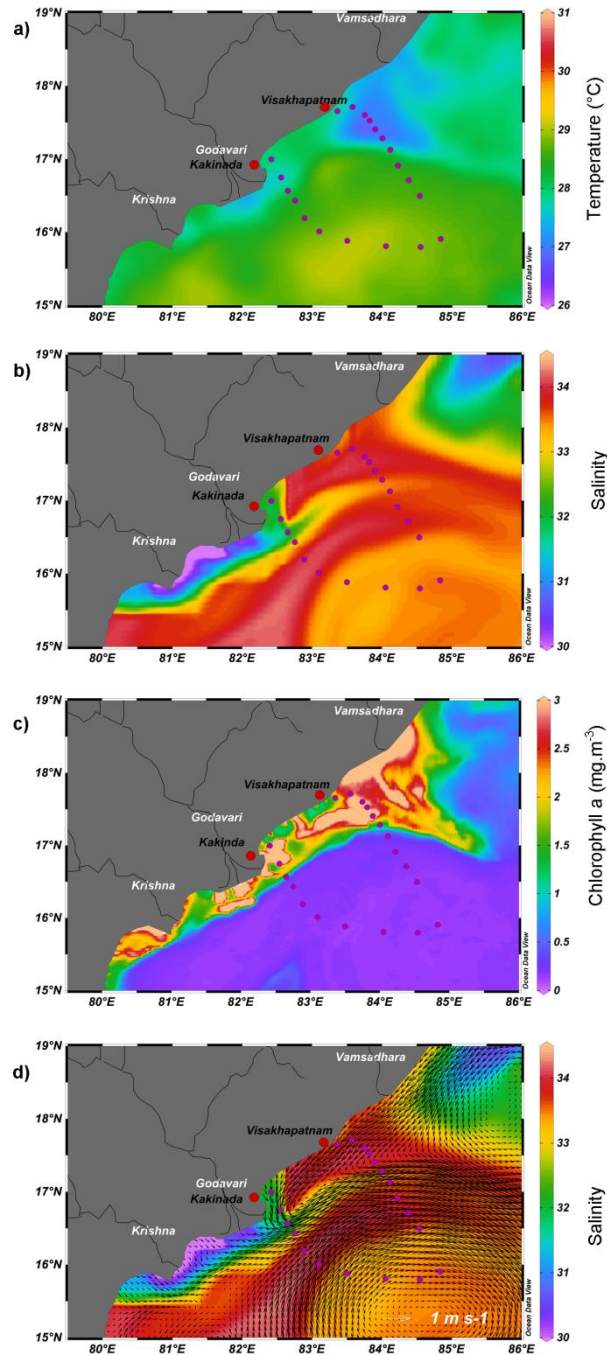


Figure – 4 a) Temperature, b) Salinity, c) Chlorophyll *a* and d) Geostrophic currents overlaid on salinity to represent the hydrography and current flow direction during the sampling period (Second week of August 2019). The presence of cool surface temperature near the coast and their spatial extension to Visakhapatnam offshore represents the offshore advection of upwelled waters from coastal regions. Low salinity was found close to the river mouth of the Godavari and Krishna and their spatial extend was found 30-40 km offshore. Upwelling band was more prominent between the Srikakulam and Kakinada. Low saline water from north and freshwater inputs from Godavari and Krishna are the northern and southern boundary of the upwelling band. Notably, low salinity water of Godavari was advected northwards by the outer periphery of the warm core eddy and the advection path was away from the coast and found ~100km from the coast in off Visakhapatnam. Low saline waters from the north and south regulated the shape of the high chlorophyll *a* layer.

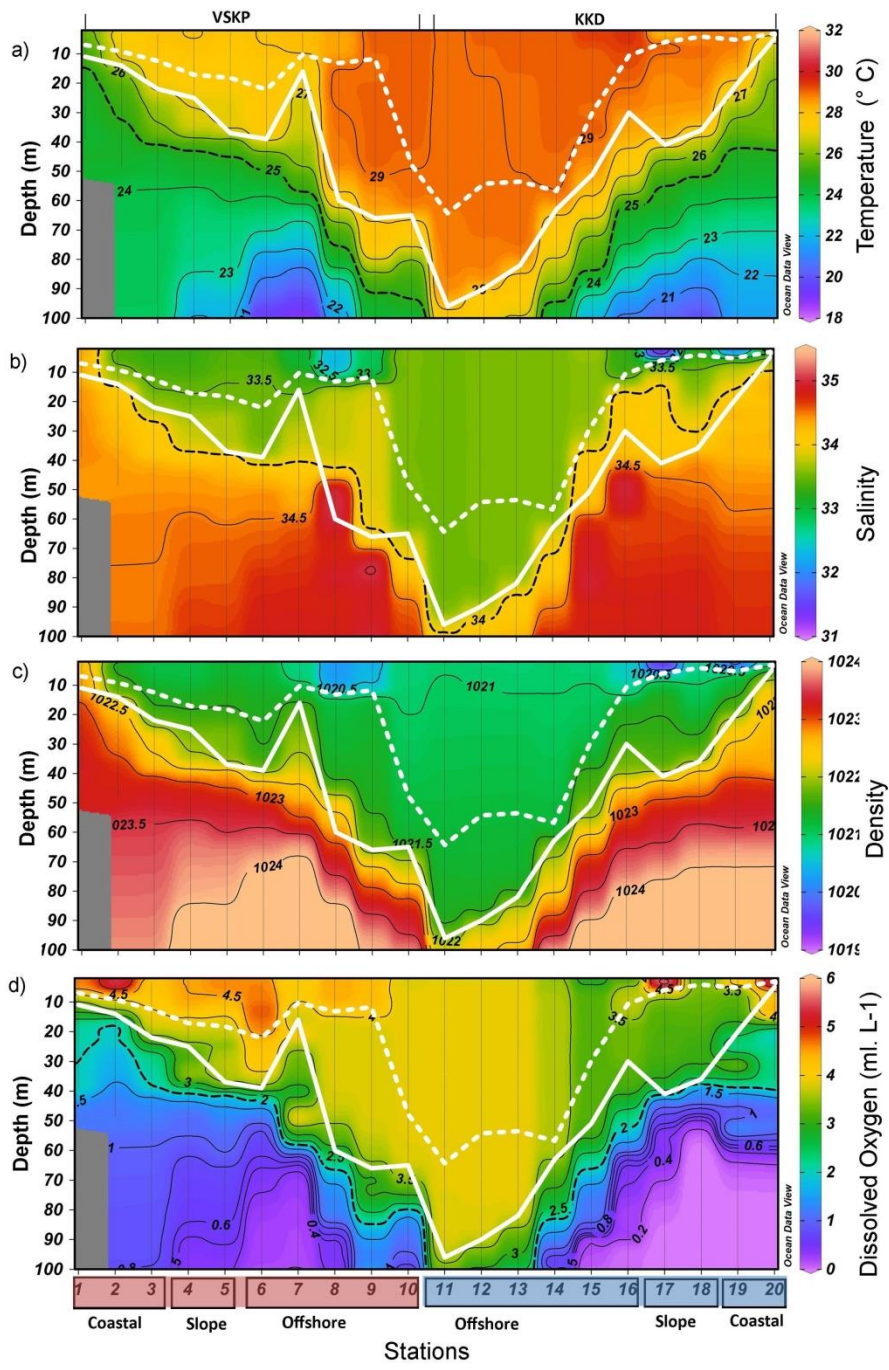


Figure 5 - Vertical distribution of a) temperature, b) salinity, c) density and d) dissolved oxygen in cross-shore sections of the Visakhapatnam (VSKP) and Kakinada (KKD). Mixed layer (dotted while lines) and Isothermal temperature layer (solid white line) were over laid on the hydrographical parameters. Relatively cool and high saline waters in the upper layers of the VSKP inshore indicating the prominent coastal upwelling. However riverine influx from the Godavari River overwhelmed upwelling and restricted the high saline cool waters within subsurface layers in the KKD. Freshwater influence is seen extended upto slope regions in KKD. Noticeably, low salinity was reported in upper layers of VSKP offshore location. Barrier layer is relatively thick in stratified upper layers (location 8 and location 9 in VSKP, coastal and slope locations of the KKD).

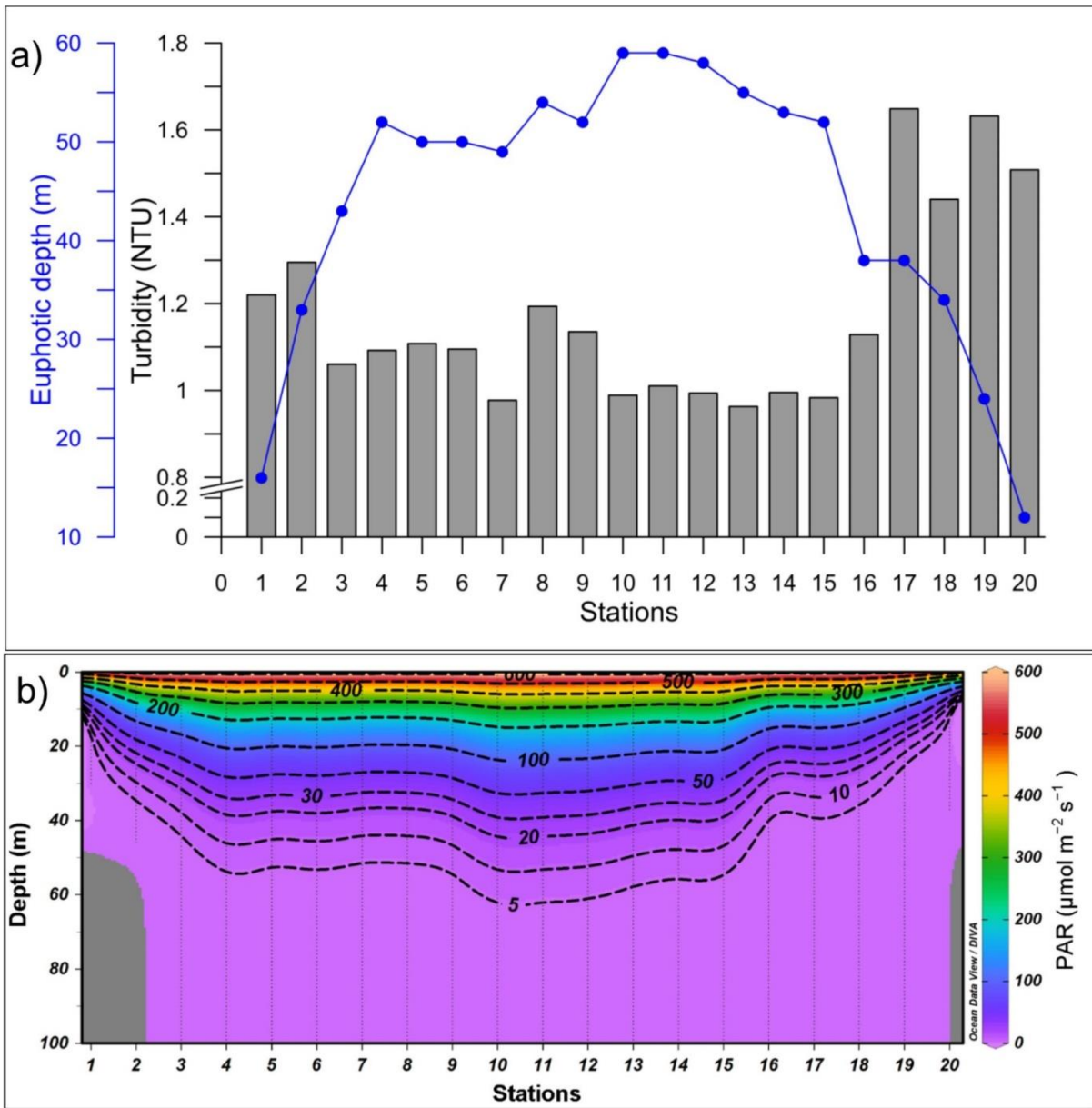


Figure 6 – (a) Variation in turbidity (Grey Bars), euphotic depth (blue line) in the study region. River influenced coastal and slope locations (17 -20) of KKD was relatively turbid results the shallow euphotic depths compare the VSKP coastal and slope locations (1 -5). b) Vertical PAR in sampling stations.

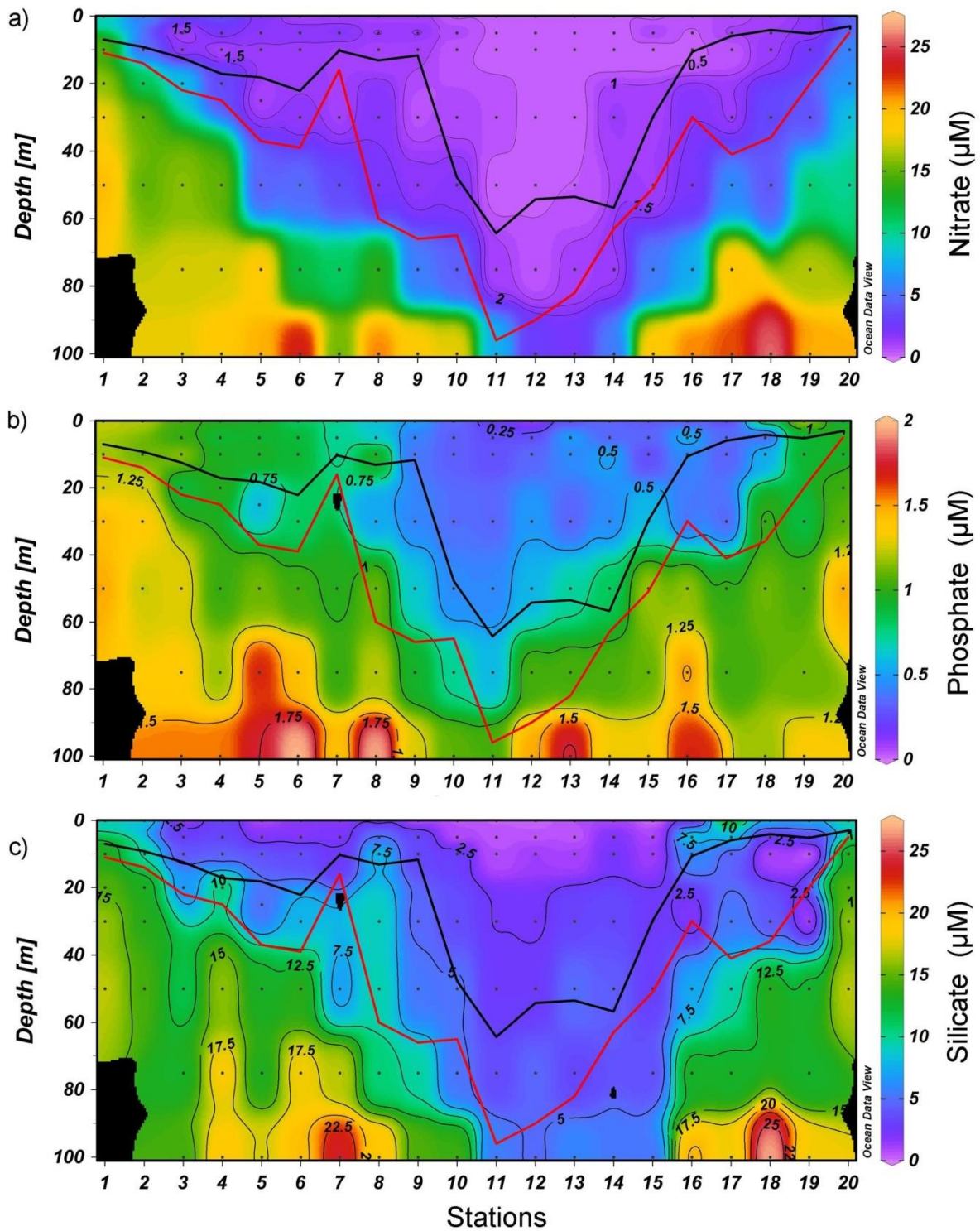


Figure – 7. Distribution of the major nutrients a) nitrate, b) phosphate, c) silicate in the study locations. The warm core eddy locations had low nutrients concentration compared to other locations. Nitrocline was extended upto depth of 80m in the warm core eddy locations. Thick black solid and pink solid lines are the Mixed layer depth and Isothermal temperature layer respectively.

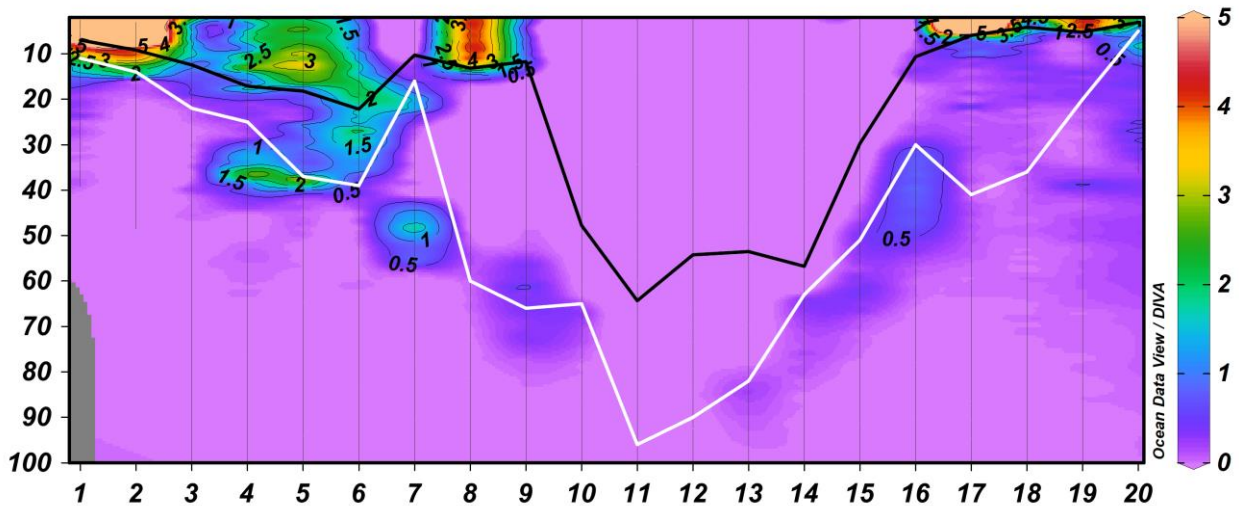


Figure – 8. Distribution of the Chlorophyll *a* in the study locations. Upper layer Chlorophyll *a* was high in inshore and coastal locations of KKD and VSKP but the magnitude was high in inshore locations of VSKP. Riverine influx increased the upper layer Chlorophyll *a* in the slope regions of KKD but this was found as the thin layer. However, upwelled waters advection increased the upper layer chlorophyll *a* vertically ~20-30m. In offshore location, upper layer Chl *a* was several folds high in upwelled advection (location 6) and low saline water advection (location 8 and 9) influenced locations of VSKP compared to KKD. Subsurface Chl *a* maxima (SSCM) was prominent in the slope regions of VSKP and it was well separated from the upper high chlorophyll layer by an intermittent low chlorophyll layer. SSCM was absent or had a less Chl *a* in riverine influenced slope locations (location 17 and 18) of KKD. SSCM was relatively deep and had less Chl *a* in offshore locations of VSKP than adjacent slope locations. SSCM was at a depth of 85-95m in the core eddy and it up sloped towards the periphery (45-67m) in the KKD transect. Black and white lines represent the mixed and isothermal layers respectively.

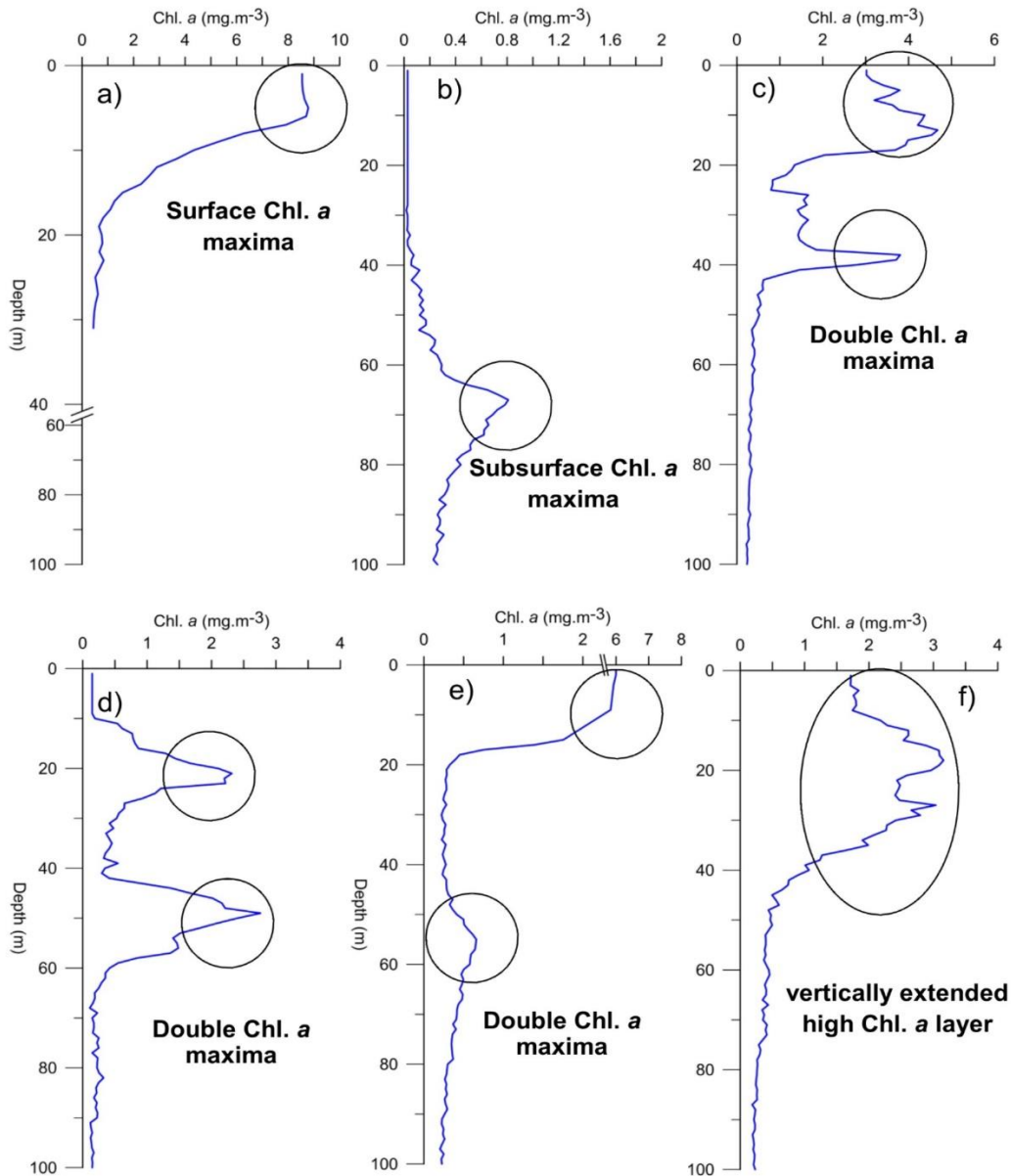


Figure - 9. Four types of Chlorophyll distributions were identified in the present study: 1). Surface Chlorophyll maxima (SCM); 2) Subsurface Chlorophyll Maxima (SSCM); 3) Double Chlorophyll Maxima (DoCM) and 4) Extended Chlorophyll Maxima (ECM). SCM and SSCM are well known Patterns in BoB. DoCM recently recognized feature from western BoB and ECM is a newly recognised pattern in WBoB. SCM is common in the inshore and coastal locations. SSCM is common in open ocean regions. DoCM has both the SCM and SSCM layer and it well separated by an intermittent low Chlorophyll a layer. Two different patterns of DoCM were reported in the present study; type I DOCM, first high Chl *a* layer in the upper layer and second in the subsurface layers, this pattern was found in the upwelled water advection influenced slope (4 and 5) locations of VSKP. In type II, upper layer had less Chlorophyll a, first high Chl *a* layer was in beneath the top layers (intermittent depths) and second high Chl *a* layer was in further deep. ECM (>1 Chl *a*) was found in location 6 and the high Chl *a* was extended from the surface to 40m without clear separation of the SSCM layers.

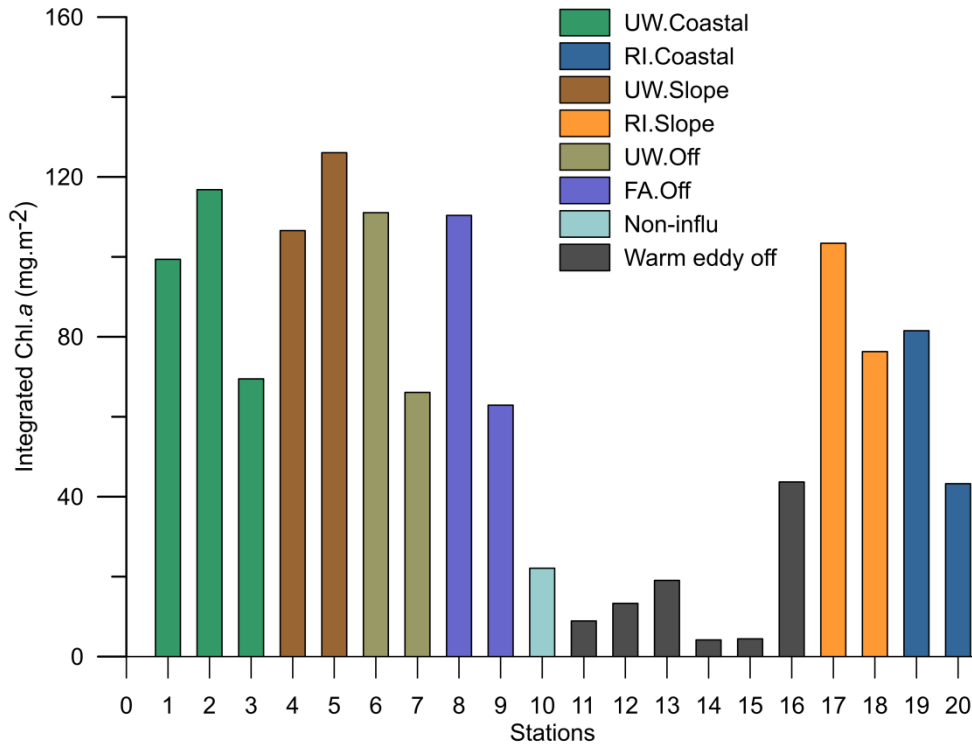


Figure – 10. Integrated Chlorophyll *a* (mg.m⁻²) in the study locations. Integrated chlorophyll *a* concentration in the coastal locations were relatively high in the VSKP. Upwelled water and low saline advection influenced offshore locations integrated chlorophyll *a* was 2 to 3 folds high compared to warm core and non-influenced locations. offshore locations. Locations 1-10 was cross shore section of Visakhapatnam and 20-11 was in Kakinada. Abbreviation in legends represents the different environmental settings: UW.coastal – Upwelled coastal locations; RI.Coast- River influenced coastal locations; UW.Slope – Upwelled water advection influenced slope location; RI.Slope- Riverine influx influenced slope location; UW.Off- Upwelled water advection influenced offshore location; FA.Off – low saline water advection influenced offshore location; Non-infl- Non influenced offshore location; Warm eddy off- Warm core eddy influenced offshore location.

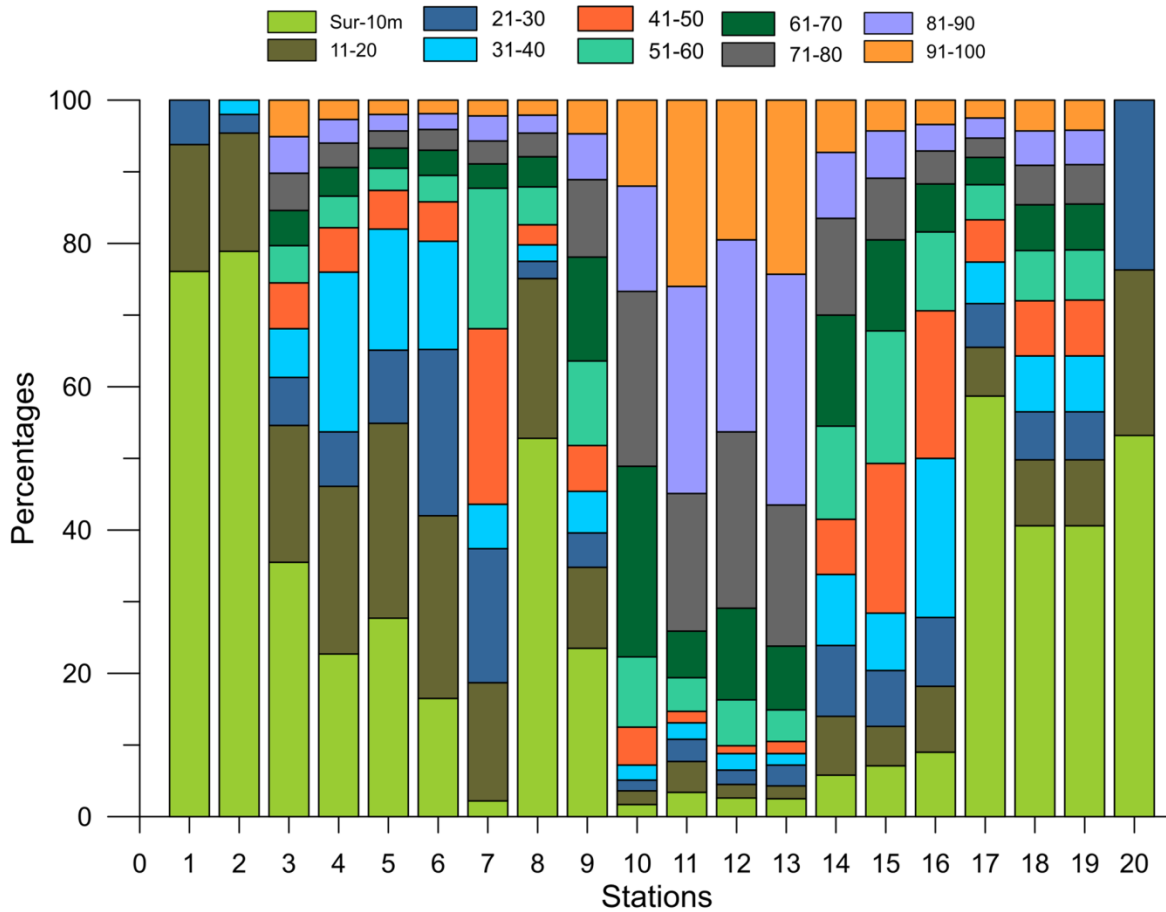


Figure – 11. Contribution of different depth layers to integrated Chlorophyll a ($\text{mg}\cdot\text{m}^{-2}$) in the study locations of 1-10 (VSKP) and 20-11 (KKD). In warm core locations (locations 11-13) upper layer contribution in total integrated Chlorophyll a was less and found the significant contribution from the deeper layers. In slope regions, Subsurface Chlorophyll a maxima layer (31-40m) contribution in total Integrated Chlorophyll a was relatively high in VSKP compared to KKD.

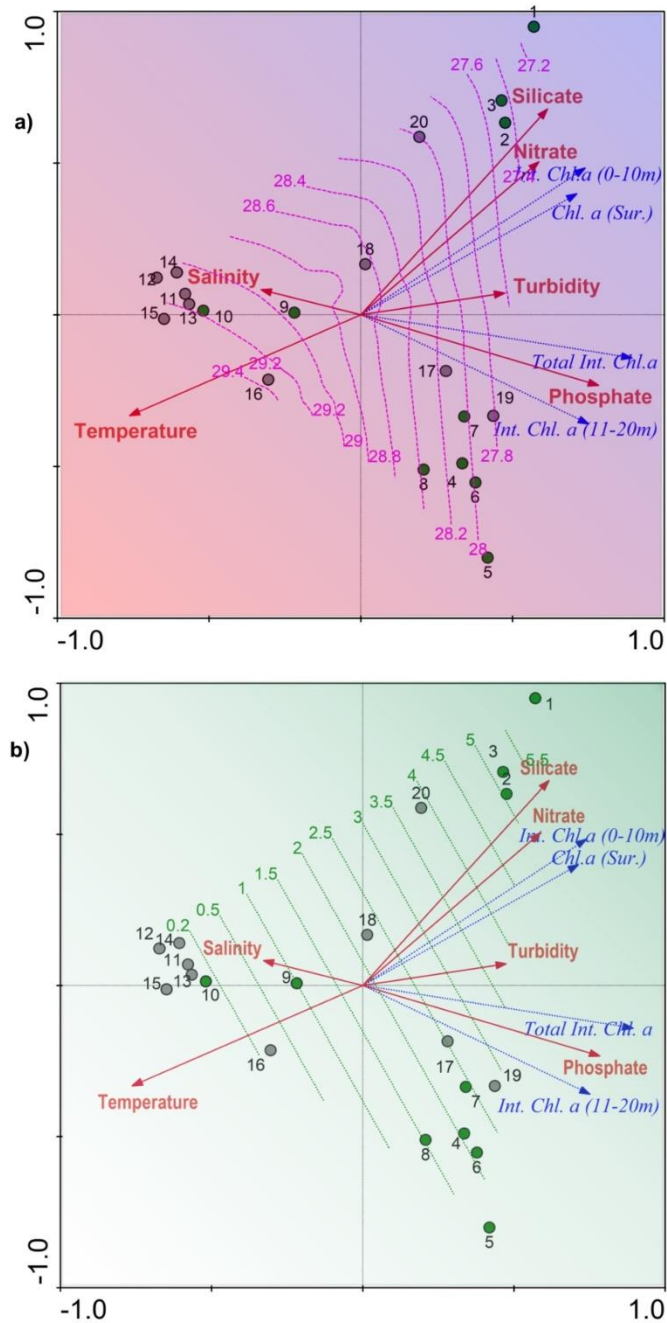


Figure – 12 . RDA triplot explains the distribution of the environmental variables (red solid lines) and biological variables (blue dotted lines) and their interrelationship in upper layer. Green circles represents the locations of the VSKP and grey filled circles represents the locations of KKD. Temperature overlaid attribution plot (pink dotted lines) and colour gradients from red to blue represents the warm to cool; Chlorophyll a overlaid attribution plot (green dotted lines) and colour gradients of the dark green to white represents the high to low Chlorophyll a. RDA triplot showed the environmental and Chlorophyll a was differed within and between the transects. Abbreviations: Chl a (Sur.)- Chlorophyll a surface; Int Chl a (0-10m) – Integrated Chlorophyll a.

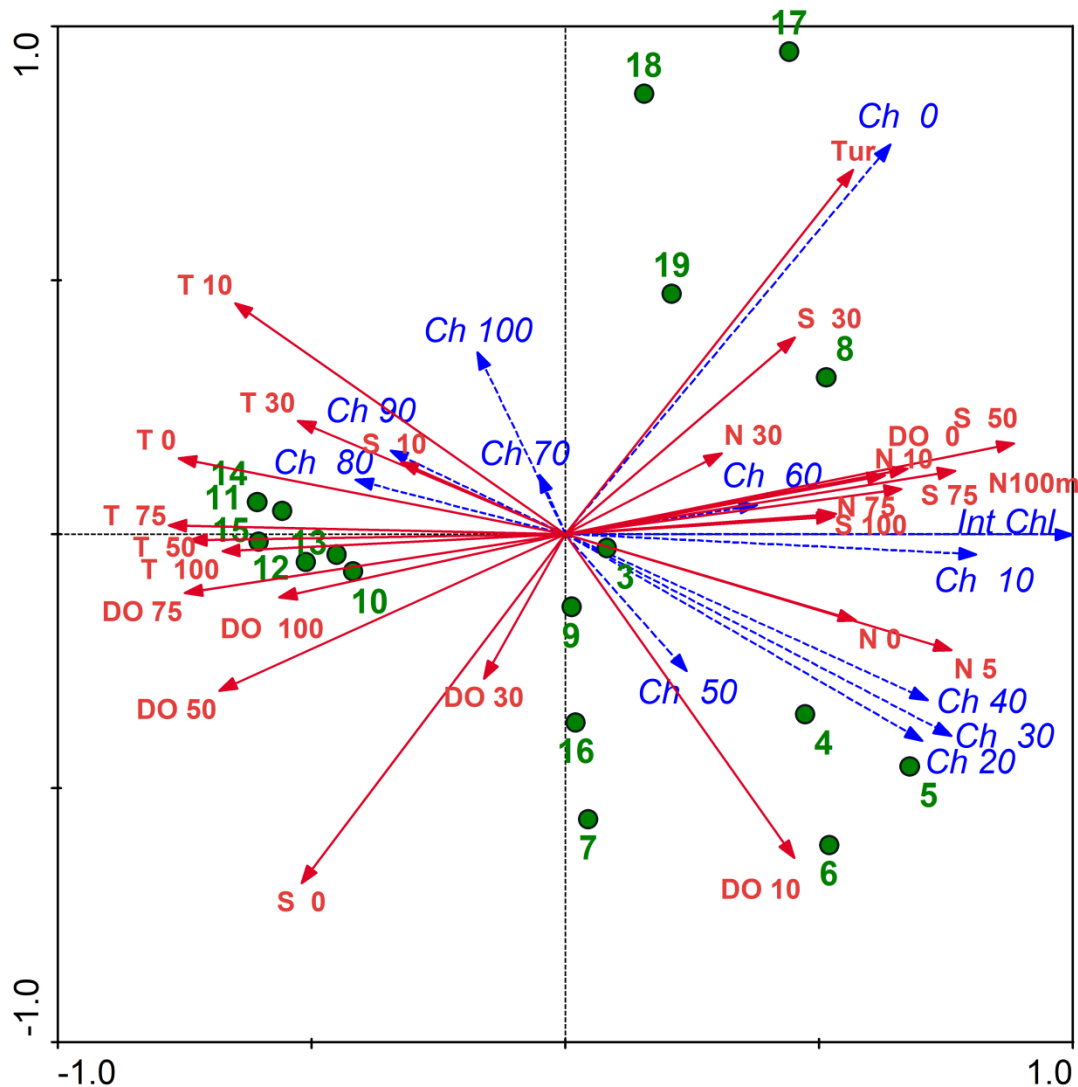


Figure – 13 –RDA triplot of water column visualising the distributional relationship of hydrographical parameters and their influence on Chlorophyll *a* distribution in various layers. Environmental variables are in solid red line and biological parameters are in the blue dotted line. Green dots represent the sampling locations. Orientation of the hydrographical parameters axes and chlorophyll *a* distribution visualized the spatial heterogeneity of the hydrobiology in upper and subsurface layers associated with prevailing hydrographical settings. Abbreviations: T = Temperature (°C); S=Salinity; DO- Dissolved oxygen (ml. L^{-1}); N= Nitrate (μM); Tur = Turbidity (NTU); Ch = Chlorophyll *a* ($\mu\text{g.L}^{-1}$); Int.Chl – Column Integrated Chlorophyll *a* (mg.m^{-2}). Number in each parameter label represents the particular parameter in that depth (example T 0 represents - Temperature at depth 0m).

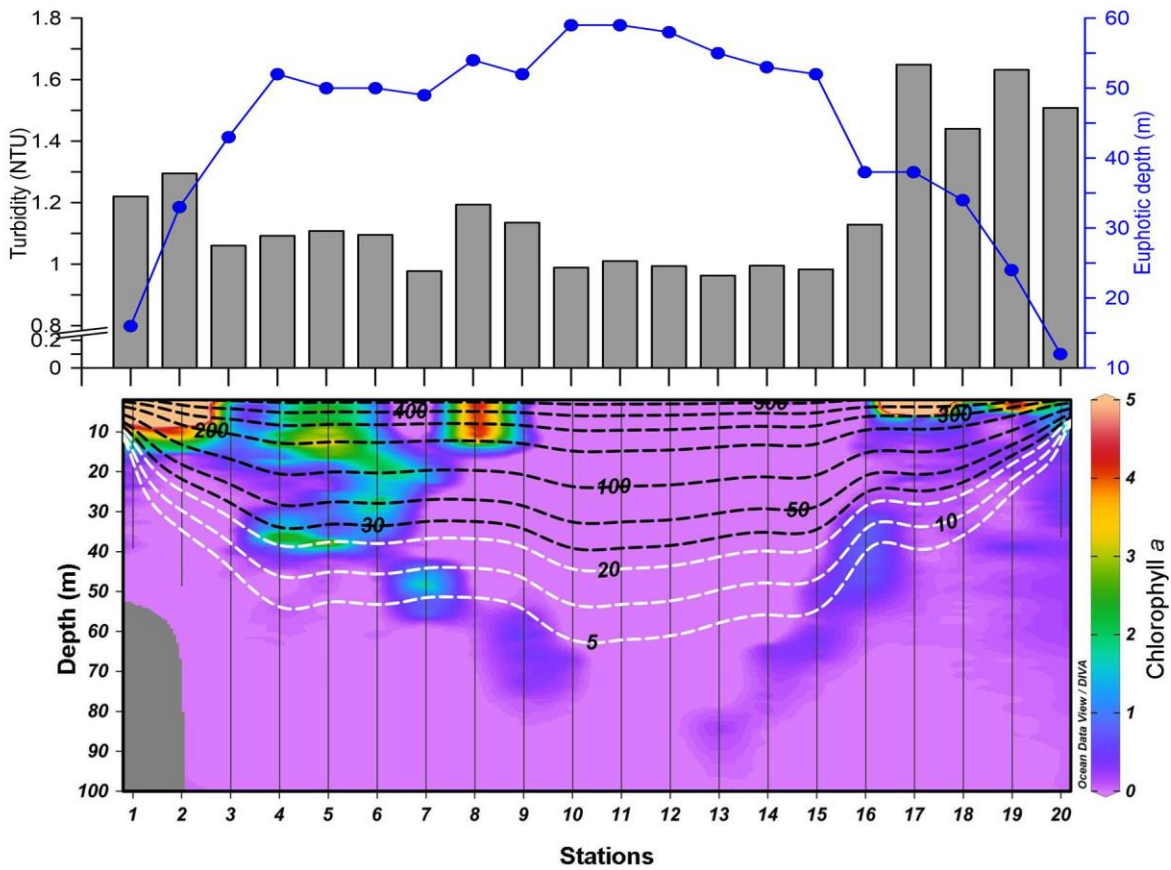


Figure – 14. The vertical distribution of the Chlorophyll *a* (Color shades) in relation to under water PAR (over laid contour lines). Turbidity (grey bars) and euphotic depth (blue lines) combined graph was placed in top panel to visualize the interference of turbidity on the penetration of light. In accordance with the upper layer turbidity, optimum light available depth for high production in Subsurface Chlorophyll *a* Maxima (white dotted contour lines - PAR: 5 - 20 $\mu\text{mol m}^{-2} \text{s}^{-1}$) was differed.

	Location	Condition	Locations	Temperature (°C)	Salinity	Turbidity (NTU)
VSKP	Coastal locations	Upwelling	1-3	27.12 ± 1.09 (25.8)*	33.68 ± 0.62 (34.39)*	1.19 ± 0.13
	Slope regions	Upwelled advection influenced	4 and 5	27.94 ± 0.10	33.37 ± 0.07	1.10 ± 0.01
	Offshore	Upwelled advection influenced	6 and 7	28.08 ± 0.08	33.23 ± 0.24	1.03 ± 0.08
		Low saline advection influenced	8 and 9	28.80 ± 0.4	32.60 ± 0.33	1.16 ± 0.18
		Non- influenced	10	29.16	33.53	0.98
KKD	Coastal locations	River influenced	19 , 20	28.72 ± 0.08	32.13 ± 0.65	1.45 ± 0.22
	Slope	River influenced	17 , 18	28.89 ± 0.19	32.04 ± 1.07	1.48 ± 0.25
	Offshore	Inner periphery of Warm core	14-16	29.02 ± 0.21	33.54 ± 0.02	1.02 ± 0.07
		Core of warm core eddy	11-13	29.05 ± 0.01	33.49 ± 0.17	0.99 ± 0.02

Table – 1. Distribution of temperature, salinity and density (mean ± SD) in the upper layer of various environmental situations of VSKP and KKD. Riverine influx altered upper layer salinity and temperature in coastal and slope regions of KKD. the coastal and slope locations of VSKP were cool and high saline compared to KKD. Offshore region of VSKP was subjected to different hydrographical settings. In upwelled water advection influenced offshore locations faced high salinity and relatively cool than warm-core eddy periphery advected low saline water impacted offshore locations. Inshore location of VSKP (*represented as bold) faced overall high saline and cool.

	Location	Condition	Nitrate (μM)	Phosphate (μM)	Silicate (μM)
VSKP	Coastal locations	Upwelling	5.78 ± 4.97	1.13 ± 0.08	7.06 ± 4.43
	Slope regions	Upwelled advection influenced	1.98 ± 0.98	0.94 ± 0.03	2.94 ± 1.37
	Offshore	Upwelled advection influenced	1.40 ± 0.46	0.80 ± 0.08	2.32 ± 0.81
		Low saline advection influenced	1.21 ± 0.29	0.58 ± 0.21	3.82 ± 2.54
		Non- influenced	0.48 ± 0.04	0.33 ± 0.01	0.72 ± 0.09
KKD	Coastal locations	River influenced	3.21 ± 1.96	0.95 ± 0.12	8.81 ± 3.62
	Slope	River influenced	1.03 ± 0.31	0.44 ± 0.21	5.62 ± 3.8
	Offshore	Inner periphery of Warm core	0.47 ± 0.25	0.38 ± 0.11	1.75 ± 0.98
		Core of warm core eddy	0.40 ± 0.05	0.30 ± 0.12	0.60 ± 0.25

Table – 2 : Nutrients distribution in upper layer (surface - 10m mean \pm SD) of various environmental situations in VSKP and KKD. Nitrate and phosphate concentration was relatively high in upwelling and upwelled water influenced coastal and slope regions compared to riverine influenced coastal and slope locations. However, silicate concentration was higher in KKD coastal and slope locations than in VSKP. Offshore nutrients concentrations were noticeably higher in the upwelled water and low saline advection influenced location of VSKP compared to their adjacent (non-influenced) location and offshore locations of KKD. Overall less nutrients were found in the core eddy locations of KKD.

	Location	Condition	Upper layer Chl <i>a</i> (mg. m ⁻³)	Total integrated Chl <i>a</i> (mg.m ⁻²)
VSKP	Coastal locations/ Shelf	Upwelling	8.52 ± 4.45 Inshore : 8.3 Near shore : 11.4	95.22 ± 23.94 Inshore : 99.38 Near shore : 116.81
	Slope regions	Upwelled advection influenced	2.79 ± 0.32	116.31 ± 13.78
	Offshore	Upwelled advection influenced	0.93 ± 1.10	88.57 ± 31.79
		Low saline advection influenced	3.80 ± 3.09	86.69 ± 33.56
		Non- influenced	0.23	22.10
KKD	Coastal locations	River influenced	4.38 ± 2.04 Inshore: 2.93 Coastal: 5.82	81.53 ± 43.25 Inshore: 43.25 Coastal: 81.53
	Slope	River influenced	8.45 ± 1.06	89.85 ± 19.15
	Offshore	Inner periphery of Warm core	0.34 ± 0.29	24.09 ± 34.28
		Core of warm core eddy	0.21 ± 0.07	13.76 ± 5.09

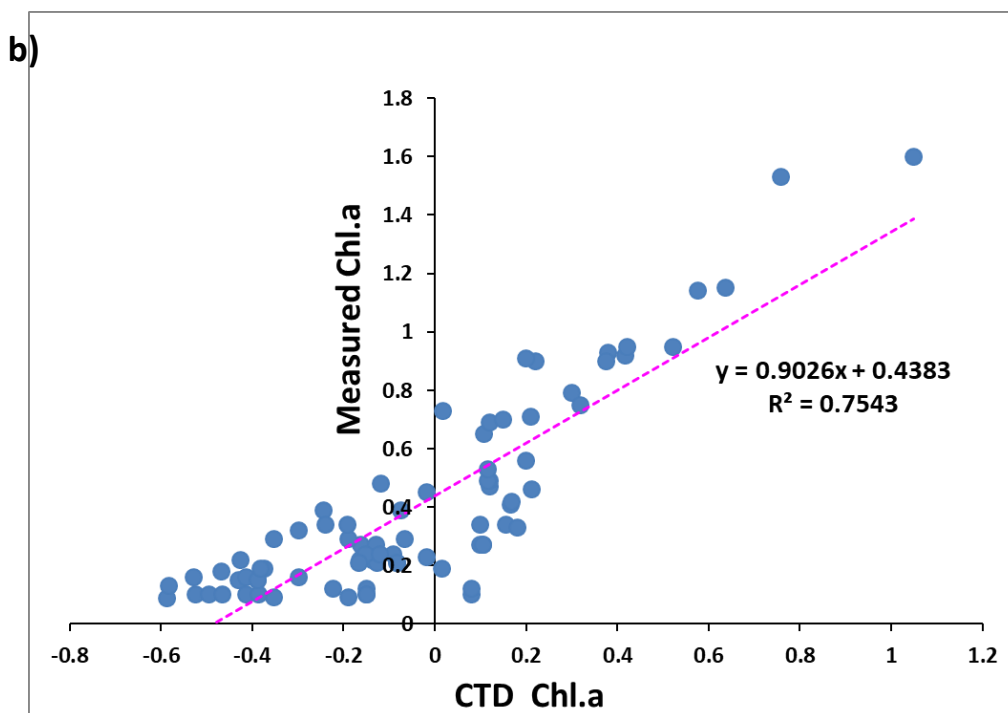
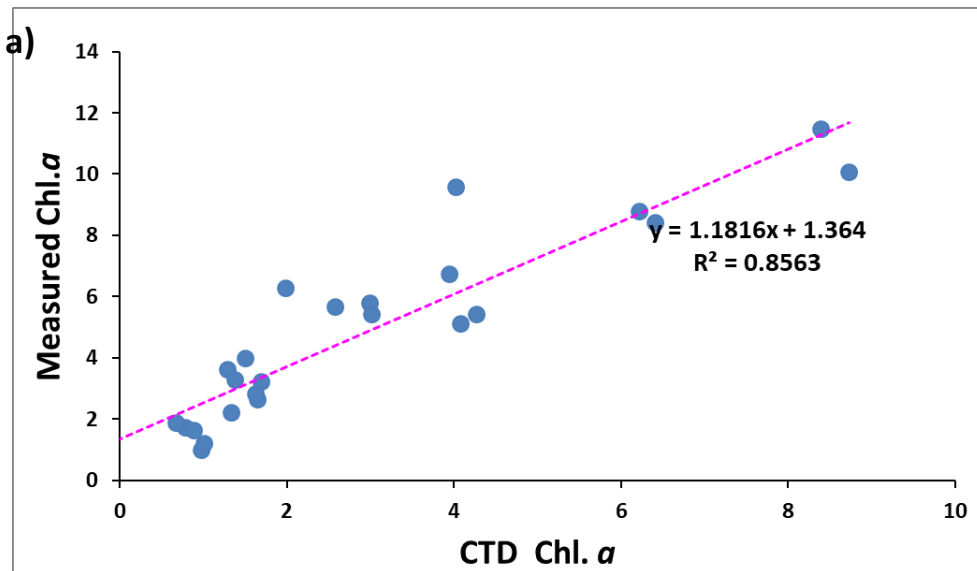
Table – 3 – Chlorophyll *a* (mg. m⁻³) and depth integrated Chlorophyll *a* concentration (mg.m⁻²) in different environmental settings during the study period.

Parameters	Resolution	Sensors	Description of the paper
Sea surface Temperature	1/12°	GLORYS12 V1 Product Reanalysis	<ul style="list-style-type: none"> The GLORYS12V1 product is the CMEMS global ocean eddy-resolving (1/12° horizontal resolution, 50 vertical levels) reanalysis covering the altimetry (1993 onward). The model component is the NEMO platform driven at surface by ECMWF ERA-Interim then ERA5 reanalyses for recent years. Observations are assimilated by means of a reduced-order Kalman filter. This product includes daily and monthly mean files for temperature, salinity, currents, sea level, mixed layer depth and ice parameters from the top to the bottom. Product name: global-analysis-forecast-phy-001-024*
Salinity	1/12°	GLORYS12 V1 Product Reanalysis	<ul style="list-style-type: none"> Model and details as per the seasurface temperature Initially we retrieved the global-analysis-forecast-phy-001-024 product for visualisation of the parameters later we retrieved the reanalysed product for better presentation Product name: global-reanalysis-phy-001-030-daily*
Daily Chl. <i>a</i>	4x4 KM	SeaWiFS, MODIS, MERIS, VIIRS-SNPP & JPSS1, OLCI-S3A & S3B for the “multi” products, and S3A & S3B only for the “olci” products.	<ul style="list-style-type: none"> Product : Multi satellite Variables: Chlorophyll-a (CHL), Primary Production (PP), Phytoplankton Functional types and sizes (PFT), Suspended Matter (SPM), Particulate Backscattering (BBP), Secchi Transparency Depth (ZSD), Diffuse Attenuation (KD490), Absorption Coef. (ADG440/CDM440) and Reflectance (RRS). Temporal resolutions: daily, monthly plus, for some variables, daily gap-free based on a space-time interpolation to provide a “cloud free” product.

			<ul style="list-style-type: none"> • Spatial resolutions: 4 km (global) or 300 meters (global coastal) • Product name: dataset-oc-glo-chl-multi-l4-oi_4km_daily-rt-v02*
Monthly Chl.a Average	4x4 KM	Multiple sensors	<ul style="list-style-type: none"> • Chlorophyll-a concentration in seawater (not log-transformed), generated by as a blended combination of OCI, OCI2, OC2 and OCx algorithms, depending on water class memberships • Product name : OCEANCOLOUR_GLO_CHL_L4_REP_OBSERVATIONS_009_093
Sea surface Height anomaly and Geostrophic currents	0.25° × 0.25°	Multiple sensors	<ul style="list-style-type: none"> • The SLA is estimated by Optimal Interpolation, merging the L3 along-track measurement from the different altimeter missions available. • This product is processed by the DUACS multimission altimeter data processing system. • Product name : SEALEVEL_GLO_PHY_L4_NRT_OBSERVATIONS_008_046* Frequency : daily

Supplementary material 1. Details of the satellite retrieved products and their resolution

Source : Copernicus : <https://data.marine.copernicus.eu/products>. *product names as per our retrieval period– August 2019. NRT data sets of were downloaded for initial analysis and reanalysed data sets were used for better presentation



Supplementary material – 2 – Regression line was created to correct CTD measured Chl *a* using measured chlorophyll *a* to obtain high-resolution vertical chlorophyll *a* data. To avoid turbidity interferences, separate regression equations were created for (a) coastal locations, b) slope and offshore regions.



Supplementary material 3. On-board collected sample photos and their qualitative representation under microscope. a) Multi-diatom bloom with discoloration was found in the coastal water of Visakhapatnam. b) *Noctiluca* swarm with slight yellowish orange colour was found in coastal locations of Kakinada and their qualitative view represents their high abundance in the collected samples.