

## Why do satellite imageries show exceptionally high chlorophyll in the Gulf of Mannar and the Palk Bay during the Northeast Monsoon?

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### Abstract

The Gulf of Mannar (GoM) and the Palk Bay (PB) are two least studied marine environments located between India and Sri Lanka. Exceptionally high chlorophyll *a* concentration in the GoM and the PB during the northeast monsoon (November –February) is a consistent feature in satellite imageries, which has been attributed to the intrusion of the Bay of Bengal (BoB) waters. The analyses of MODIS and field chlorophyll data collected from 30 locations in the Indian sector of GoM and PB in January 2011 showed significant overestimations in the satellite data. This error was much higher in the PB (60 - 80%) as compared to the GoM (18-28%). The multivariate analyses evidenced that the exceptionally high satellite chlorophyll in the PB is contributed largely by turbidity, CDOM and bottom reflectance. The paper cautions that though MODIS is superior in estimating chlorophyll *a* in optically complex waters, there are still chances of overestimations in regions like PB.

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Key words: chlorophyll, phytoplankton, multivariate analysis, sediments, turbidity, satellite imagery, Gulf of Mannar, Bay of Bengal

## 1. Introduction

Satellite remote sensing has significantly improved our understanding of complicated ocean dynamics. One such application is the use of satellite chlorophyll *a* (hereafter chlorophyll) to identify synoptic oceanographic features (Dwivedi et al. 2006; Jyothibabu et al. 2010; Rao et al. 2011). However, it is fundamental that there are chances of misinterpretation of satellite chlorophyll in optically complex coastal waters (Sathyendranath et al. 1989). Considering the bio-optical properties, Morel and Prieur (1977) proposed two kinds of waters. In Case 1 water (oceanic), the optical properties are primarily determined by phytoplankton with insignificant influence from colored dissolved organic matter (CDOM) and degradation products of detritus. In case 2 water (coastal), the optical properties are largely determined by other constituents such as suspended particles, and CDOM and its concentrations do not co-vary with phytoplankton concentration. In case 1 waters, the bio-optical properties governed by phytoplankton show a shift in the blue to green ratio of upwelling irradiance with respect to the difference in concentration of chlorophyll (Morel and Prieur 1977; Prieur and Sathyendranath 1981). However, this color ratio criterion is unreasonable for the detection of chlorophyll in case 2 waters due to the presence of suspended sediment particles and dissolved organic matter that absorb blue light and strongly interfere with the upwelling irradiance leading to over estimations (Sathyendranath 2000).

The GoM and PB are located between India and Sri Lanka (Figure 1a). The GoM is relatively deep (av. depth 100m) and extends ~190 km along the Indian coastline (~19600 km<sup>2</sup>). On the other hand, the PB is an enclosed shallow basin (av. depth 9m), which extends ~260 km along the Indian coastline (~13500km<sup>2</sup>). The GoM is connected to the Arabian Sea (AS) in the west and PB to the Bay of Bengal (BoB) in the east. The Rameswaram (Pamban) island of India, Ramsethu (Adams Bridge) and Mannar Island of Sri Lanka, act as physical barriers that inhibit exchange of waters between the GoM and the PB (Figure 1b). The PB is a large reservoir of suspended sediments brought from the BoB during the northeast monsoon period (Figure 2a). The PB is known for extensive sea grass beds in shallow areas where the bottom substratum is sandy or silty (Sridhar et al. 2010; Manikandan et al. 2011). Based on the above oceanographic features, we hypothesize that there could be significant overestimations in the satellite chlorophyll *a* in the GoM and the PB.

The ocean currents around the Indian subcontinent during the northeast monsoon period are characterized by southward flowing East India Coastal Current (EICC) along the western BoB (Figure 2b). Part of the EICC carrying low saline, cool and turbid BoB waters intrudes into the PB (Rao et al. 2011). This feature is evident in the SST distribution presented in Figure 3a and also in the surface current pattern presented in Figure 3b. The high level of sediments under low wave action causes deposition and emergence of sand banks in the PB (Chandramohan et al. 2001). The GoM receives sediments mostly from the PB and also from rivers such as Thamiraparani, Vembar and Vaippar. However, on an annual scale, the sediment flux in the PB is several

orders of magnitude higher than that in the GoM (Sanilkumar et al. 2002). Satellite chlorophyll images presented in earlier studies show exceptionally high concentration in the PB during the northeast monsoon, which has been a consistent feature in CZCS (Yapa 2000), SeaWiFS (Vinayachandran et al. 2004; Rao et al. 2011), IRS P4 (Sarangi et al. 2008) and MODIS (present study) (Supplementary evidence 1). Although some of the earlier researchers cautioned about the possibility of over estimation of satellite chlorophyll in the PB (Yapa 2000, Vinayachandran et al. 2004; Sarangi et al. 2008), there is no scientific information available so far on the actual causes of this exceptionally high satellite chlorophyll in the PB. In this context, we analyzed the MODIS satellite chlorophyll in the Indian sector of the GoM and PB during the northeast monsoon period in relation to relevant environmental properties.

## 2. Materials and methods

The present study is based primarily on field sampling carried out in January 2011 in 30 locations, 15 each in the Indian sector of the GoM and the PB (Figure 1a). The sampling locations were distributed in 10 transects (15 locations each in the GoM and the PB), oriented almost perpendicular to the Indian coastline. In each location, a portable CTD was used to measure the physical parameters such as temperature and salinity. Water samples were collected from the surface waters (0.2m) using 5L Niskin samplers. The chlorophyll *a* was measured using a calibrated Turner lab fluorometer (accuracy 0.01mg) following the standard procedure (UNESCO 1994). The turbidity of the surface waters was measured using a Eutech E120 Turbidity meter (accuracy 0.01NTU) following nephelometric principles. Suspended particulate matter (SPM) was measured using gravimetric methods employing a sensitive electronic balance (accuracy 0.1mg). Weekly mean 4km chlorophyll data, satellite reflectance at 555 nm, and Colored Dissolved Organic Matter (CDOM) were downloaded from MODIS aqua ([www.giovanni.gsfc.nasa.in](http://www.giovanni.gsfc.nasa.in)). The satellite data were selected in such a way that the field sampling period was covered in the weekly mean satellite data. The satellite data of 8-16 January 2011 correspond to our field sampling in the GoM and data of 17 -26 January 2011 correspond to our field sampling in the PB. The satellite data were processed in Arc GIS software for overlying with the field sampling locations. The satellite data coinciding with the field locations were selected and in a few cases, where the satellite data points did not exactly coincide with the field sampling locations, the mean of the satellite data points lying very close to the field sampling locations were selected. The data were tested for the normal distribution and then segregated according to their locations in the GoM and PB based on their similarity in quantities of various parameters using XL stat software. Redundancy Analysis (RDA) was carried out using the entire data and presented in Triplots for understanding the two dimensional representations of various parameters and their interrelationships. The RDA is similar to canonical correlation analysis that finds relationships among several sets of variables following linear correlations (Birks 1998; Leps and Smilauer 2003).

### 3. Results and discussion

During the northeast monsoon, the GoM was characterized by higher salinity and Sea Surface Temperature (av.  $32 \pm 0.58$  and av.  $26.55 \pm 0.49$  °C respectively) as compared with the PB (av.  $28.9 \pm 1.42$  and av.  $25.45 \pm 0.61$  °C respectively). The synoptic view of the spatial difference in Sea Surface Temperature (SST) between the GoM and the PB is evident in MODIS imagery (Figure 3a). Taking into account the salinity and SST as two discriminating parameters in the study area, we segregated the sampling locations into two separate clusters representing the GoM and the PB (Figure 4a). The relative positions of the locations in the clusters are based on their salinity and SST values (Figure 4b). All study locations other than 12 and 22, which had the lowest salinity and SST respectively, formed clear segregation into the GoM and the PB regions. Location 22 was in the PB in the region of low saline plume and location 12 was in the GoM near to the Pamban Pass, which was influenced by the intrusion of PB waters (Supplementary evidence 2). The spatial distribution of various environmental parameters is very clear in the bubble plots (Figure 4 c – h). It shows the overlaid data of turbidity, reflectance at 555 nm, SPM, CDOM, satellite and *in-situ* chlorophyll on spatially segregated locations of the GoM and PB based on their temperature and salinity. The distribution of environmental parameters evidenced that the PB had distinctly higher turbidity (av.  $4.38 \pm 2.16$  NTU), reflectance (av.  $1.19 \pm 0.51 \times 10^{-2}$  sr<sup>-1</sup>), SPM (av.  $7.69 \pm 2.89$  mg L<sup>-1</sup>) and CDOM (av.  $4.12 \pm 1.58$ ), whereas the GoM had lower turbidity (av.  $1.76 \pm 1.38$  NTU), reflectance (av.  $0.57 \pm 0.37 \times 10^{-2}$  sr<sup>-1</sup>), SPM (av.  $5.21 \pm 2.56$  mg L<sup>-1</sup>) and CDOM (av.  $2.42 \pm 1.41$ ). Exceptional levels of turbidity (56 NTU) were also found in the northeastern location in the PB (location 28), but these values are not included in the mean (Figure 4c). The spatial distribution of *in-situ* and MODIS chlorophyll presented contrasting results (Figure 4 g-h). The *in-situ* chlorophyll was higher in the GoM (av.  $1.79 \pm 1.62$  mg m<sup>-3</sup>) as compared with the PB (av.  $0.76 \pm 0.49$  mg m<sup>-3</sup>) whereas, the MODIS chlorophyll was higher in the PB (av.  $2.94 \pm 1.0$  mg m<sup>-3</sup>) as compared to GoM (av.  $2.00 \pm 0.74$  mg m<sup>-3</sup>). A direct comparison of the MODIS and field chlorophyll in the study locations showed relatively small difference in values in the GoM as compared with the PB (Figure 5). The error in the MODIS satellite chlorophyll was much higher in the PB as compared to the GoM (Figure 5, Table 1). A clear inshore – offshore difference in the error percentage was evident, which was more in the GoM as compared to the PB (Table 1).

Chlorophyll is a biological indicator very useful in the management of coastal bio-resources, but its accurate estimation in optically complex waters using satellite remote sensing is a real challenge (Muller Karger et al. 2005). Although tremendous effort has been applied to improve the satellite data, there are still uncertainties in shallow coastal waters where optical properties are determined primarily by other constituents such as suspended sediments, CDOM, and bottom reflectance (Muller Karger et al. 2005; Cannizaro et al. 2006). Empirical, semi-empirical and analytical methods are generally used to estimate the concentration of

chlorophyll by satellite measurements from the backscattered light at three wavebands centered at 443nm, 520nm and 550nm, covering the blue and green regions of the visible spectrum. The radiances that fall on the water column are not just reflected from the sea surface, but are selectively absorbed, scattered and reflected by the suspended particles present in the water column and eventually back scatter to the atmosphere. This backscattered light contains information leading to the quantitative estimates of chlorophyll present in the upper few tens of meters in oceanic waters, and a relatively shallower layer in inshore waters. In optically shallow waters, turbidity and shallow bottom can contribute to the observed reflectance in the red region of the spectrum (Muller Karger et al. 2005; Cannizaro et al. 2006). It has been shown that a small error in CDOM can significantly affect the blue absorption and cause large errors in satellites chlorophyll retrievals (Muller-Karger et al. 2005). In optically complex waters, band ratio algorithms often fail (Hu et al. 2003) and in such cases semi-analytical algorithms provide better results (Carder et al. 1999; Lee et al. 1999). The accuracy of satellite chlorophyll data in optically complex coastal waters can be improved further using regionally fine-tuned algorithms as the properties of Case 2 waters significantly vary in space and time (Hu et al. 2003). This seems to be very relevant in the case of the present study area, the GoM and PB, where there are large spatial and seasonal differences in water column characteristics due to the peculiar geography and seasonally reversing ocean currents (Rao et al. 2011; Jagadeesan et al. 2013). Therefore, it is important to derive optical parameters required in models such as the spectral slope of the CDOM absorption, particle back scattering, bottom reflectance considering the local variability in the GoM and the PB.

The results of multivariate RDA analysis are presented in triplot (Figure 6) in which the relative directions of the environmental parameters arrow approximate their linear correlation. Arrows pointing in the same direction correspond to variables having high positive correlation, whereas arrows of variables with a high negative correlation are oriented in opposite directions. The sample points are projected perpendicular to the arrows of environmental variables and this enables us to follow the approximate order of samples in the increasing gradient of environmental variables when proceeding towards the arrow tip and beyond it. Before the Triplot ordination model is fitted, all parameters are centered and standardized and therefore the origin of the ordinate system (central point) corresponds to the average value of environmental variable in that sample and the angle between parameter arrows approximate their linear correlations. Monte Carlo test carried out shows that the RDA Triplot ordinations used in the present study are significant (F-ratio: 4.750; P=0.002). There is a clear segregation of sampling locations into the GoM (left hand side) and the PB (right hand side) in the Triplot. The field chlorophyll showed increasing gradients towards the left hand side (GoM side) whereas, the satellite chlorophyll showed increasing gradients towards the right hand side of the plot (PB side). The field chlorophyll shows positive relationship with salinity and temperature and depth, which clearly indicate that the higher values of these parameters were found in the GoM region. The MODIS chlorophyll showed a significant positive

relationship with several mutually interlinked parameters such as SPM, turbidity, reflectance and CDOM, whereas it has a significant inverse relationship with SST, Sea Surface Salinity (SSS) and depth (Figure 6b). The MODIS reflectance shows a significant positive relationship with turbidity, CDOM; and a significant negative relationship with depth. These indicate that CDOM, turbidity and bottom reflectance, have significant influence on the MODIS chlorophyll in the PB during the northeast monsoon period. The spatial image of the MODIS reflectance (555nm) and chlorophyll in the PB match each other and thus strongly support the above observation (Figure 7).

MODIS is equipped with spectral bands specifically designed for measuring chlorophyll fluorescence relative to a baseline (chlorophyll fluorescence line height algorithm) (Lettier and Abbot 1996). However, this algorithm has limitations due to the variation in chlorophyll fluorescence efficiency in space and time (Muller Karger et al. 2005). Therefore, fluorescence efficiency data combined with other bio-optical algorithms derived from regional oceanographic features could be a better option to improve MODIS chlorophyll data in the GoM and the PB. Earlier validation effort for satellite data (IRS P4) in the GoM and the PB was restricted mostly to the fair weather season (May) and/ or based on a very limited field samples (Selvavinayakam et al. 2003; Dey and Singh 2003). Therefore, earlier approaches could not account properly for the spatial as well as seasonal hydrographic features of the GoM and the PB. This is particularly important in the light of our recent understanding on the seasonal hydrography of the GoM and the PB (Rao et al. 2011; Jagadeesan et al. 2013).

Even though we have fairly clear understanding of the large scale circulation around India and Sri Lanka, very little is known about the ocean currents in the GoM and the PB. Recent studies evidence that the East India Coastal Current (EICC) brings low saline and cold northern BoB waters into the PB through the Palk Strait (Rao et al. 2011; Jagadeesan et al. 2013). This intruded BoB waters control the suspended sediment distribution in the study area during the northeast monsoon. The PB has shallow waters with extensive sea grass meadows in regions where the sea bottom is sandy or silty (Sridhar et al. 2010; Manikandan et al. 2011). The high suspended sediments and sea grass meadows are potential sources of CDOM in coastal marine environments (Stabenau et al. 2004). Therefore, as evident in the RDA triplot, the high satellite chlorophyll in the PB is caused largely by the shallowness, high suspended sediments intruded from the BoB and CDOM contributed by the sea grass meadows. The present paper recognizes the far reaching applications of ocean color data, but brings to the light a clear case of overestimation of chlorophyll in the southeast coast of India and cautions the scientific community to exercise the necessary care when considering the satellite chlorophyll data for oceanographic interpretations in these regions. Since the water column properties of the GoM and the PB change significantly during different seasons caused by the reversing ocean currents, it is our future interest to analyze how these oceanographic features influence the satellite chlorophyll estimations during other seasons.

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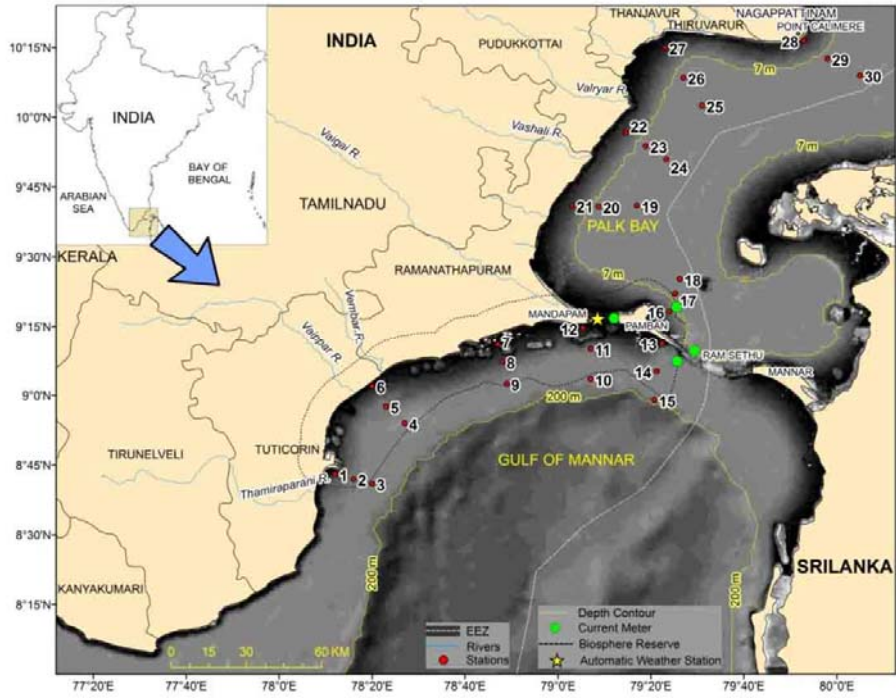


Figure 1a – Study area. Locations 1-15 and 16-30 represent the GoM and the PB respectively. Locations of current meter deployment for validating MIKE 21 simulated current in Figure 2 b is also shown

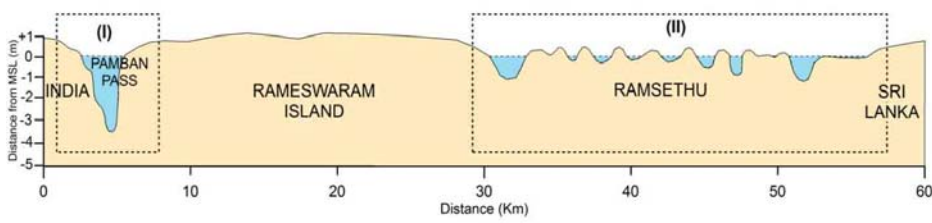
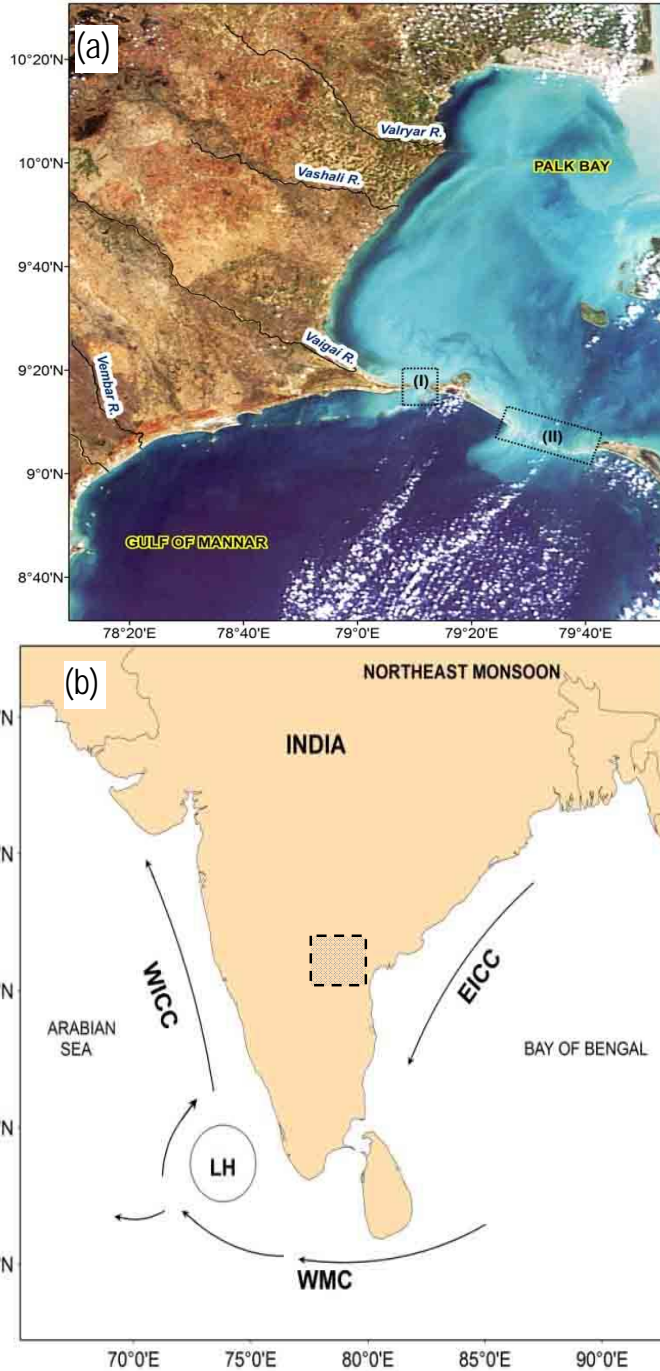
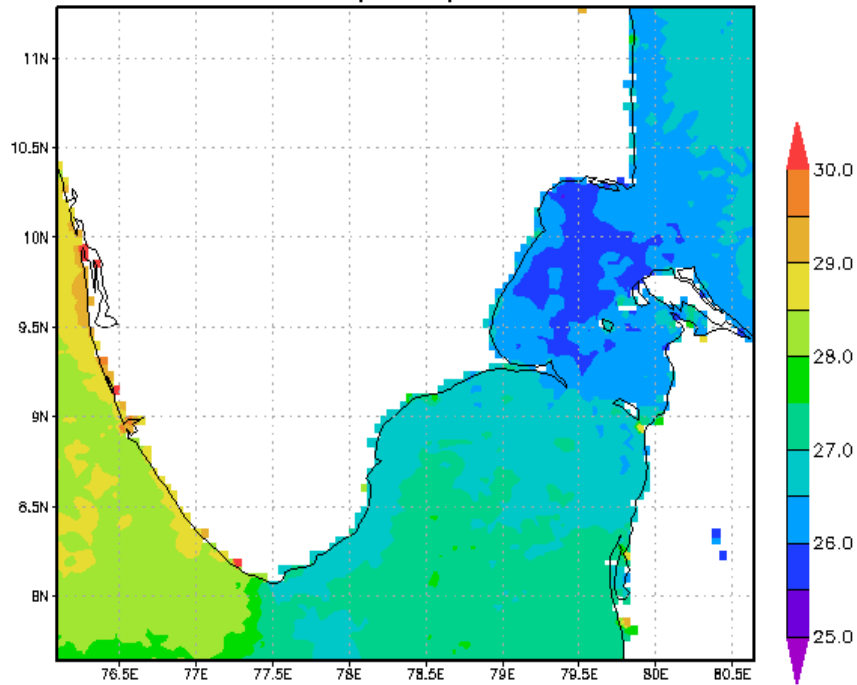


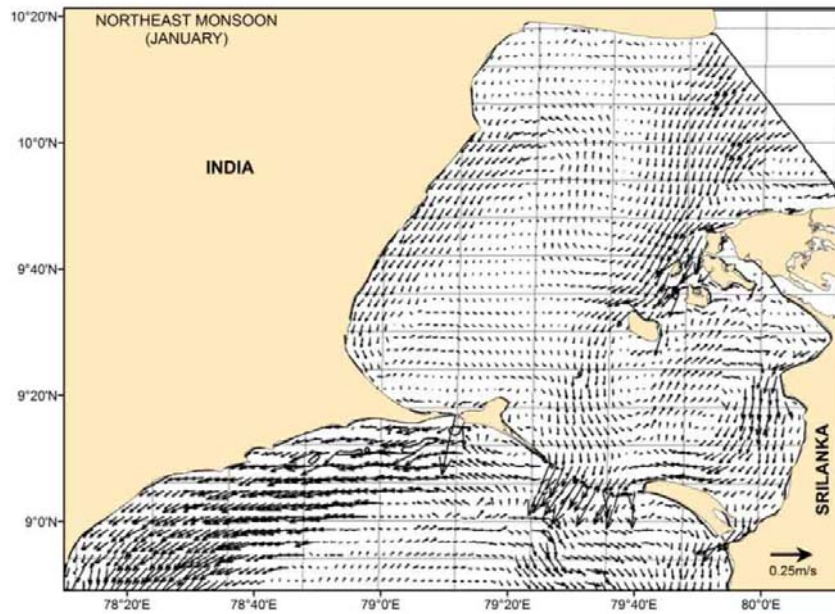
Figure 1b - Diagrammatic representation of the sea bed from Mandapam (India) to Mannar Island (Sri Lanka) based on ADP measurements in the Pamban Pass (Square I) and naval hydrography chart No. 358 in the Ramsethu Region. Also see similar representation in Sivalingam (2005).



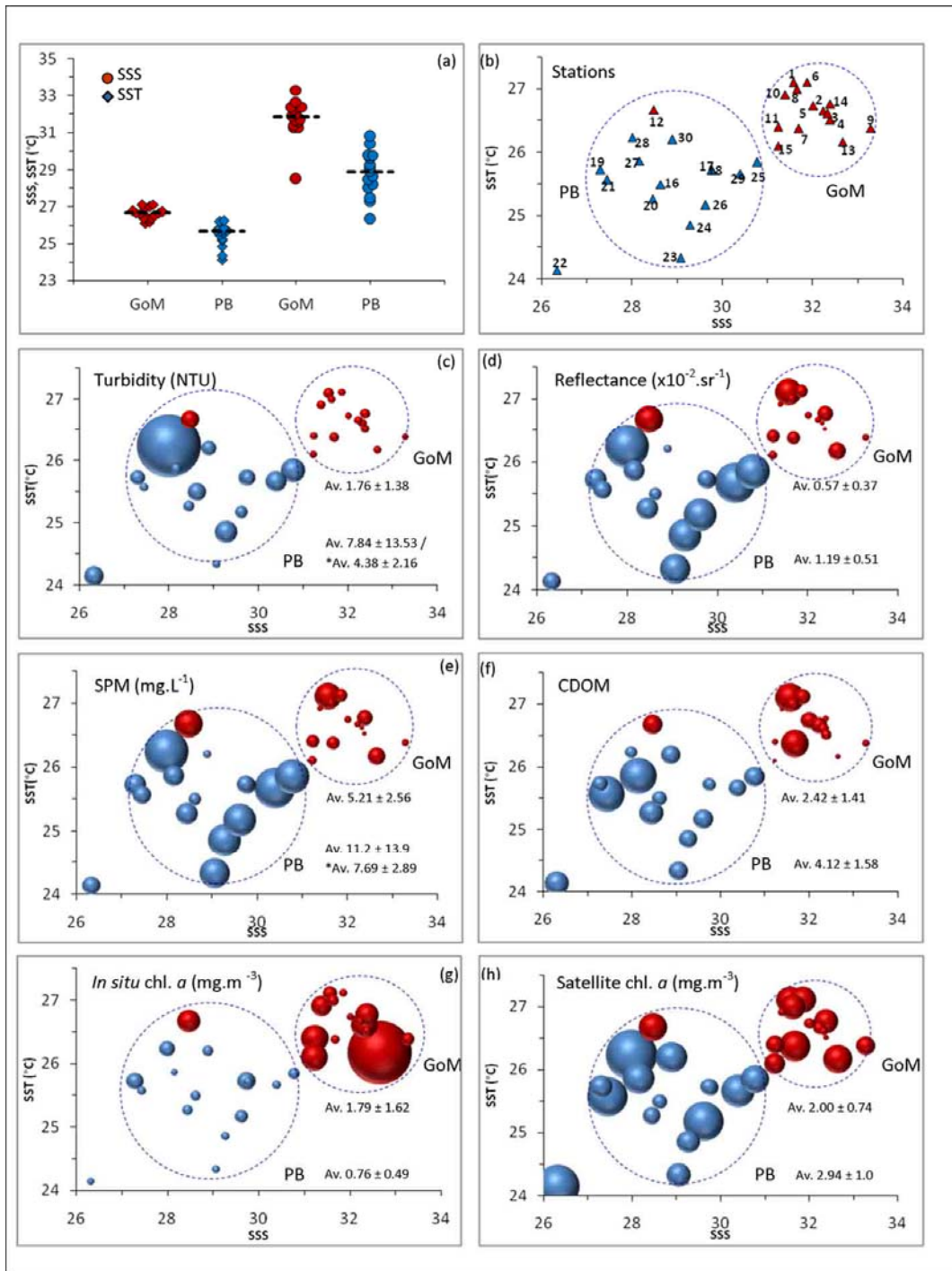
**Figure 2** – (a) MODIS -TERRA imagery showing extensive sediment plumes in the PB in January ([www.visibleearth.nasa.gov](http://www.visibleearth.nasa.gov)). The movement of sediment plumes from the PB to GoM through (I) Pamban Pass and (II) Ramsethu is also evident (b) diagrammatic representation of the coastal circulation around the Indian subcontinent during the northeast monsoon. The current study area (GoM and PB) are shaded in rectangle with dotted line border. Abbreviations: EICC- East Indian Coastal Current, WMC – Winter Monsoon Current, LH – Lakshadweep High, WICC – West India Coastal Current.



**Figure 3a** – Spatial distribution of monthly mean SST (°C) in the GoM and PB. The intrusion of cool coastal BoB waters into the PB driven by EICC is evident in the figure.



**Figure 3b** - The MIKE 21 simulated pattern of currents in the study area. The currents are generally weak in the PB.



**Figure 4** – Segregation of (a & b) locations based on temperature and salinity distribution in the GoM and the PB, (c-h) overlaid data of relevant parameters showing noticeable spatial difference in their distribution in the GoM and PB. In bubble plots (c-h), the size of the bubbles indicates the proportionate quantity of the parameters. \* indicate mean value without considering the exceptional value

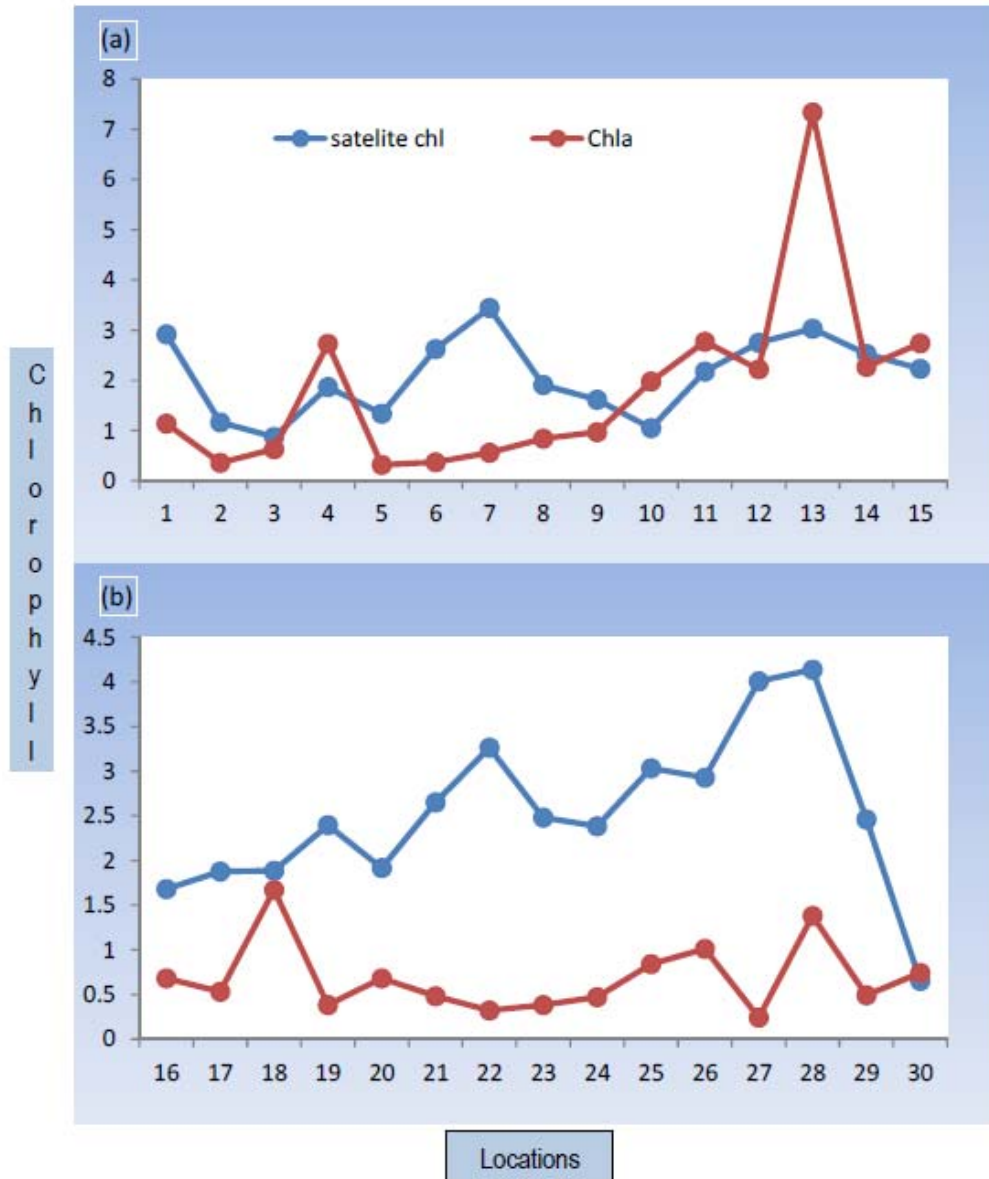
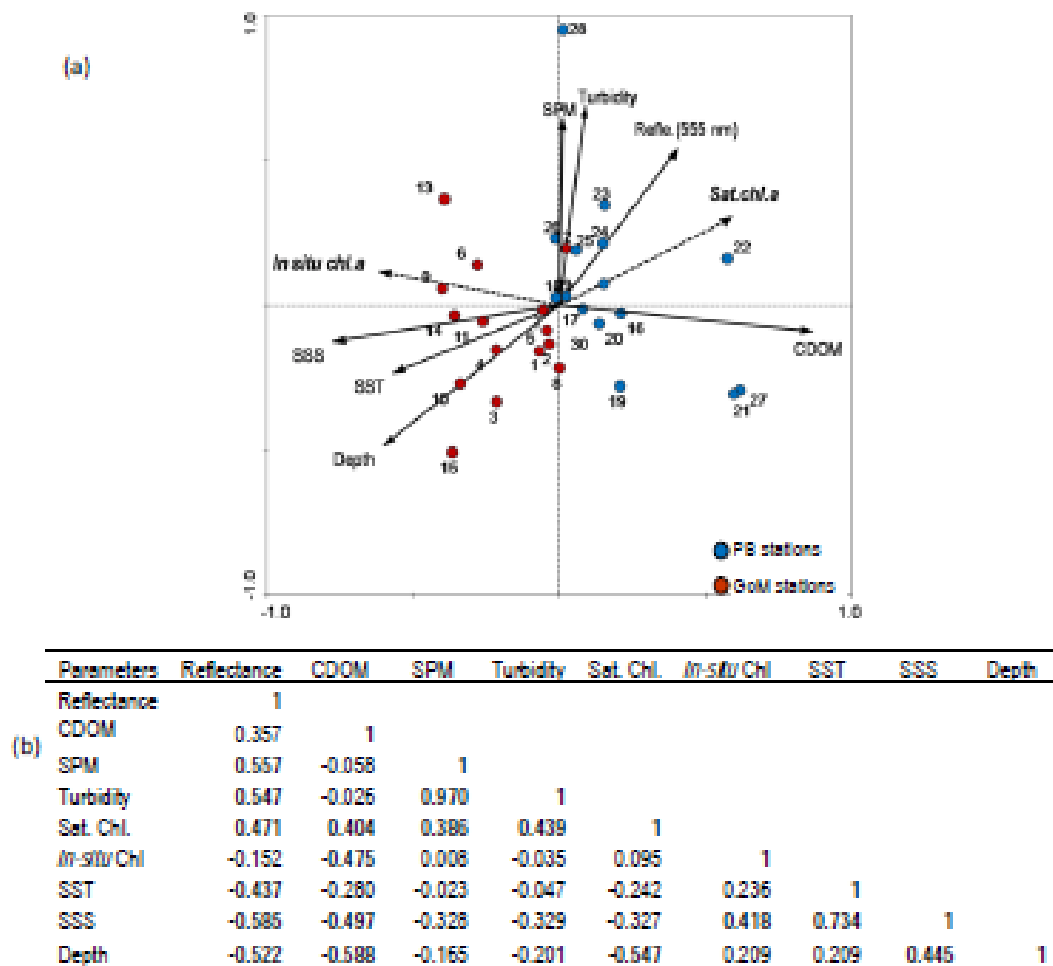
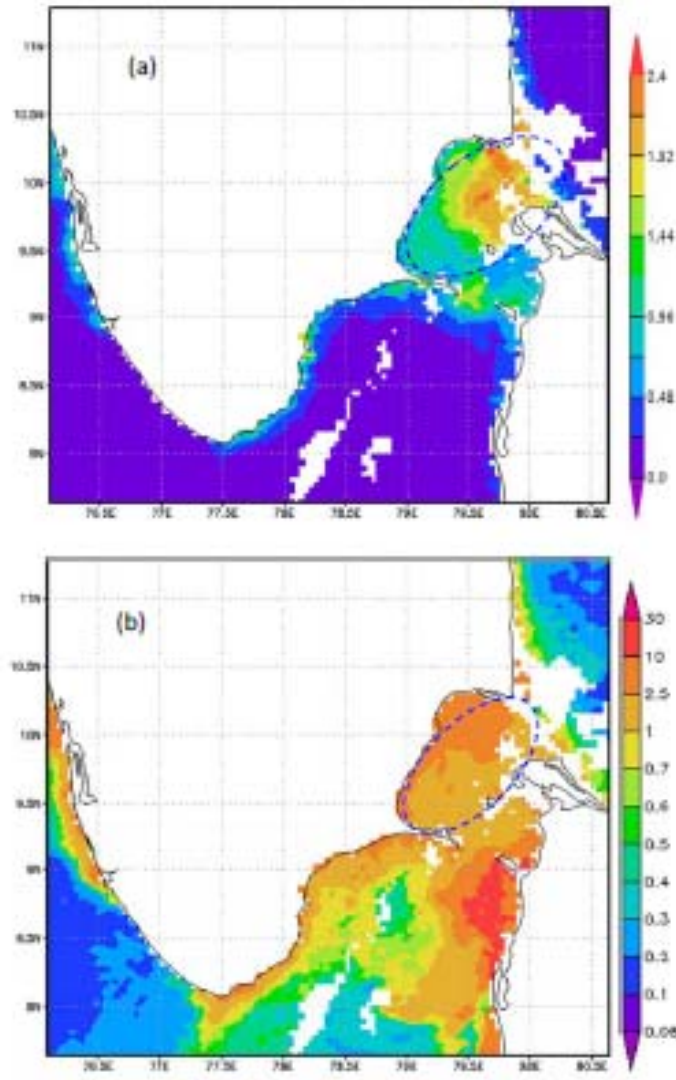


Figure 5- Comparison of MODIS satellite and *insitu* chlorophyll ( $\text{mg m}^{-3}$ ) in the (a) GoM and (b) PB. The deviation from *insitu* measurements was more prominent in the PB as compared to the GoM.



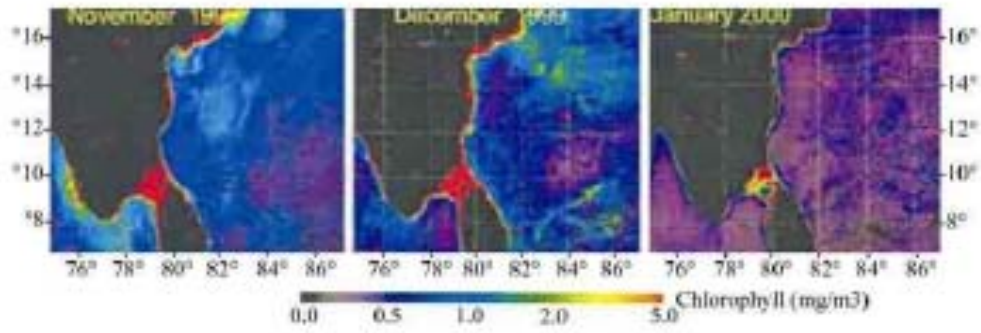


**Figure 6 (a)** RDA Triplot showing interrelationship of field and satellite chlorophyll with other hydrographic factors. Sampling stations are displayed by points and environmental variables are shown by arrows. Abbreviations: SSS - Sea Surface Salinity, SST- Sea Surface Temperature, SPM-Suspended Particulate Matter, Refle- Reflectance at 555nm, CDOM- Colored Dissolved Organic Matter. **(b)** – Correlation coefficient ( $R^2$ ) and significance between parameters projected in the Triplot as arrows. Bold numbers indicate a valid significance ( $p < 0.05$ ).

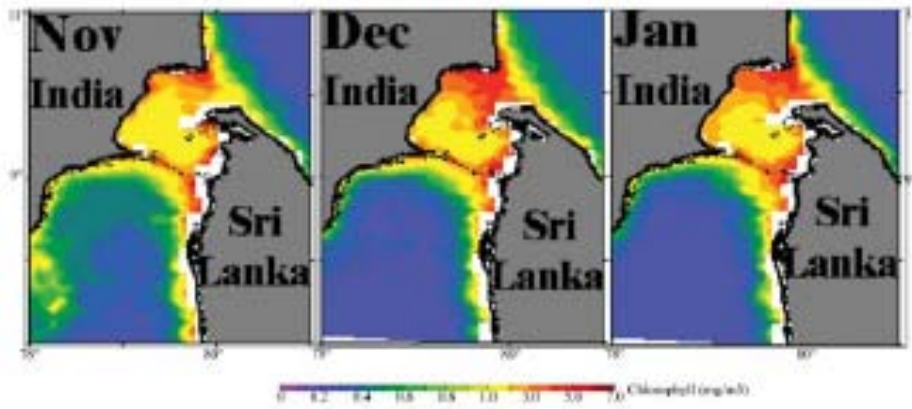


**Figure 7** - MODIS satellite weekly imagery (17-28 Jan. 2011) showing (a) reflectance at 555 nm ( $10^{-2} \text{ sr}^{-1}$ ) and (b) chlorophyll a ( $\text{mg m}^{-3}$ ).

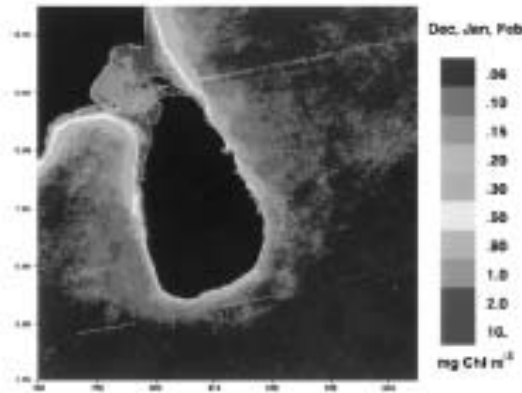
Supplementary evidence 1



IRS P4 OCM (Sarangi et al., 2008)



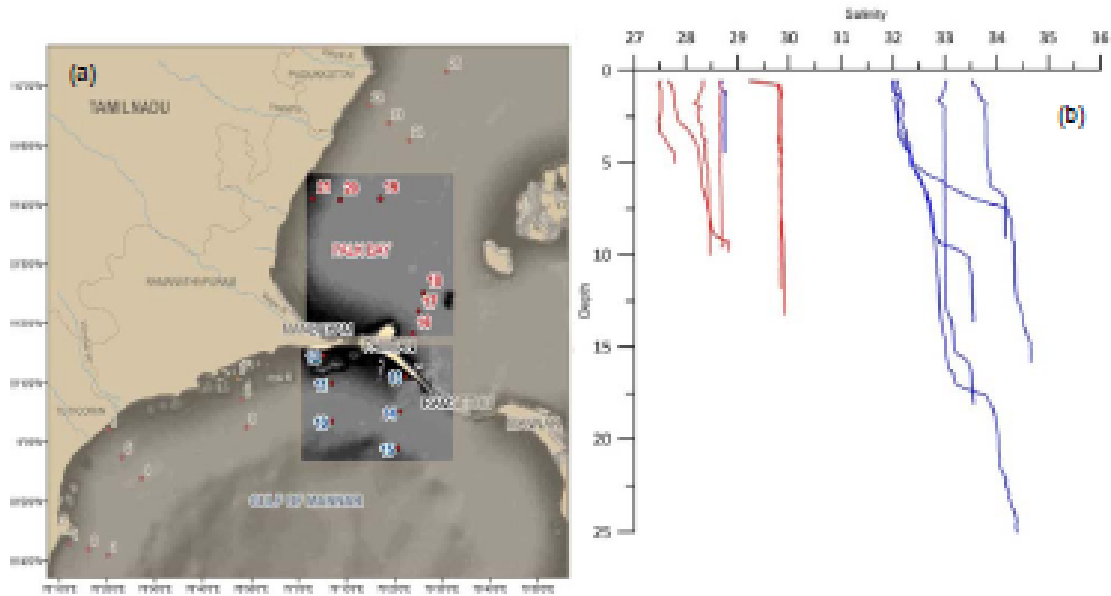
SeaWiFS (Rao et al., 2011)



CZCS (Yapa 2000)



## Supplementary evidence 2



Vertical distribution of salinity in (a) two transects on both sides of the Ramsethu considered for vertical salinity structure during the northeast monsoon. The locations in blue and red color represent the GoM and PB respectively. The marked difference in salinity levels between the GoM and PB was clear during the study period. However, the salinity in location 12 in the GoM had comparable salinity as that of the PB as evident in the vertical profiles in right panel (the blue line clustered with the red lines). This is due to the intrusion of PB waters into the GoM through the Pamban pass as evident in figure 4.

Region	Depth (m)	Turbidity (NTU)	SPM (mg L <sup>-1</sup> )	CDOM	In-situ chl. <i>a</i> (mg m <sup>-3</sup> )	Sat chl. <i>a</i> (mg m <sup>-3</sup> )	Mean error (%)
Coastal (GoM)	5.64 ± 2.34	2.02 ± 1.45	7.08 ± 3.0	3.53 ± 2.30	2.33 ± 2.89	2.95 ± 0.31	21
<b>Coastal (PB)</b>	<b>6.148 ± 2.06</b>	<b>14.32 ± 23.60</b>	<b>16.08 ± 24.8</b>	<b>5.75 ± 2.28</b>	<b>0.62 ± 0.46</b>	<b>3.15 ± 1.02</b>	<b>80</b>
Near coastal (GoM)	13.64 ± 2.02	1.22 ± 0.51	3.87 ± 2.29	2.63 ± 1.18	1.31 ± 1.14	1.82 ± 0.57	28
<b>Near coastal (PB)</b>	<b>9.88 ± 2.15</b>	<b>3.68 ± 1.79</b>	<b>8.4 ± 3.15</b>	<b>3.49 ± 0.95</b>	<b>0.62 ± 0.24</b>	<b>2.33 ± 0.44</b>	<b>73</b>
Off shore (GoM)	22.68 ± 6.14	1.27 ± 0.43	4.72 ± 1.30	1.23 ± 0.81	1.81 ± 0.98	1.53 ± 0.56	18
<b>Off shore (PB)</b>	<b>11.28 ± 1.12</b>	<b>5.73 ± 1.82</b>	<b>9.12 ± 2.44</b>	<b>3.39 ± 0.67</b>	<b>0.82 ± 0.51</b>	<b>2.07 ± 0.89</b>	<b>60</b>

**Table 1** – The distribution of various significant parameters in the study area. The decrease in percentage error in satellite chlorophyll from coastal to offshore is evident in both GoM and PB regions. PB values are shown in bold to show high error percentage of satellite chlorophyll there.