Nitrate algorithm development and remote sensing observations along the north-west Bay of Bengal coastal waters

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Abstract

The development of nitrate algorithm has been carried out using in situ collected water samples from the coastal water along Odisha and West Bengal coast, in northwest Bay of Bengal region along the stations Digha, Chandipur, Dhamra, Paradip and Astaranga. The monthly-cum-seasonally sampled datasets have been collected during July 2014-March 2016 period. The water samples have been analysed to retrieve the parameters; chlorophyll, nitrate and SST for algorithm development. During the pre-monsoon/summer season (March-June), the functions linear, paraboloid and gaussian have been applied to the datasets for 3-dimensional regression. For only surface samples (99 points) regression analysis, the coefficient of determination R^2 value with linear, paraboloid and gaussian found to be 0.457, 0.579 and 0.612. So, the gaussian function observed to be performing best regression between the 3-parameters with least standard error of estimate 15.662. This result is different from our earlier studies along Tamilnadu and Andhra coastal water, where paraboloid function fit was valid for the developed nitrate algorithms. So, we have attempted to generate nitrate images using satellite datasets. The Oceansat-2 OCM derived chlorophyll and Modis-Aqua SST have been utilized to retrieve the modelled nitrate images during March 2017 and satellite derived nitrate data has been compared with limited number of in situ cruise data during March 2017 and cloud covers have been the limitation for validation. The chlorophyll and nitrate features are observed to be matching in the satellite images.

1.0 Introduction

Nutrient is the most important abiotic factor which is directly or indirectly associated with the processes of marine ecosystem. The role of nutrients in the ocean is to support the food chain and its availability largely determines the diversity of phytoplankton (Choudhury & Pal, 2010; Sahu et al, 2016). There should be steady supply of nutrients for productivity, of oceanic environment. Among all the macronutrients, nitrogen (N) is the most common element to limit the primary and secondary production in marine ecosystems (Howarth and Marino, 2006). Nitrogen input to the sea is either through natural or anthropogenic sources. Anthropogenic sources include ground water and river input, sewage discharge and industrial runoff (Marsh 1977). The natural sources include nitrogen fixation (Wilkinson et al. 1984) and decomposition of organic matter contributed by the land habitat (Manasrah et al. 2006). Nitrate is the dominant nitrogen source strongly influencing growth of phytoplankton and thereby regulating the coastal primary productivity (Sarangi et al, 2011). Primary production is also influenced by two of the most important characteristics of seawater viz. temperature and salinity – together they control its density, which is the major factor governing the vertical movement of ocean waters. As we know phytoplankton pigment chlorophyll-a and other pigments are responsible for photosynthesis, which takes place in sun light and the primary production and new production takes place using CO_2 and nitrogen as source. The production of other components like NH_3/Urea occur through export/regenerated production in the water column in addition to carbon and NO_3^-. This has been new area of research in the Indian water using *in situ* measurements, models and remote sensing satellite data to study in synoptic scale. The rate of N_2 fixation and the estimated flux of NO_3^- to the euphotic zone need to be studied.

In the euphotic zone, the presence of phytoplankton has a significant impact on temperature-nitrate relationships. The incident solar radiation causes seawater to be warm; it also simultaneously provides the sufficient light for photosynthesis, which leads to assimilation of nitrate by phytoplankton (Goes et al., 2000). For this reason, inverse relationships between sea surface temperature (SST) and nitrate concentrations are generally observed; however, these relationships are strongly influenced by the regional biogeochemical characteristics and hydrodynamic conditions and therefore reveal a high spatial and temporal variability. Several methods have been developed to determine the presence and concentration of nitrates in the euphotic layer from SST (Dugdale et al., 1989; Kudela and Chavez, 2000; Morin et al, 1993). Some work has been done to estimate nitrate concentration from nitrate-temperature relationships (Kamykowski and Zentara, 1986; Sherlock et al., 2007) or to estimate nutrient fields from remotely sensed data (Kamykowski et al., 2002; Switzer et al, 2003). Consequently, empirical algorithms derived from the nitrate-SST relation- ships have been used for a long time, but most of the time their applicability has been limited to restricted periods and areas because of the time and space-varying nature of these relationships (Morin et al, 1993; Sathyendranath et al., 1991). Goes et al. (1999) proposed the inclusion of chlorophyll a concentration in the equation, as variations in the phytoplankton content can account for a large part of the variations in the nitrate- temperature relationships. For Indian water along Tamilnadu and Andhra coasts, works have been carried out to measure the in situ data and model nitrate basing on chlorophyll and SST for the first time (Sarangi et al, 2011, Sarangi et al, 2015, Poornima et al, 2015).

Current work focusses on the development of the nitrate algorithm in the north-western part of the Bay of Bengal, encompassing the in situ measured datasets from the coastal water stations of Odisha coast during 2014 to 2016 and has been modelled with nitrate algorithm and for the first time nitrate images have been generated using satellite datasets for this region. Bay of Bengal also shows wide range of seasonal variability in nitrate depending on the external inputs, cyclones and algal blooms etc. The present study was attempted to evaluate the potential of ocean color data (chlorophyll-*a* and SST) for basin scale monitoring of sea surface nitrate in the southwest Bay of Bengal.

2.0 Materials and method

2.1 Study Area

The Bay of Bengal is activated by the cyclonic winds, storms, gyres and sea surface is rough compared to the Arabian Sea (Burkill et al., 1993; Madhupratap et al., 2003, Sarangi et al, 2008). The Bay of Bengal connects a number of rivers along Odisha coast and receives about 6.6% of total global river fluxes (UNESCO, 1979). The river Devi, Mahanadi, Dhamra (combination of Brahmani and Baitarani), Budhabalanga and Champa connects with the BOB at Astarang, Paradip, Dhamra, Chandipur and Digha sampling stations respectively. The climatic condition of the study area is tropical resulting highest temperature in April and May. It experiences three major seasons viz. Pre-monsoon (March-June), Monsoon (July-October) and post-monsoon (November-February). The tidal condition of our study area is mixed semidiurnal type and shows southward movement of ocean water current. This area is wave dominated during monsoon and tide dominated during non-monsoon periods. Bay of Bengal is less studied and shipboard nitrate measurements fall far short of the space and time scales required for modelling and climate research. The study area contained five stations covering 55 substations, regular bi-monthly samplings were made at 0-10 km distance from the shore with 1km interval. These sampling stations were fixed by taking consideration of their geographical locations, such as off the location of river flux, off industrial discharges and critical habitats etc. The areas covered the north west part of Bay of Bengal locations, viz. Digha (21°37′27.5″N and 87°33′21.2″E) Chandipur (21°27′10.4″N and 87°04′9.02″E), Dhamra (20°48′39.9″N and 86°58′23.6″E), Paradip (20°17′31.54″N and 86°43′34.07″E) and Astarang (19°56′55.4″N and 86°23′36.7″E).

2.2 In situ sample collection and analysis

For the nitrate algorithm related study, samples from surface water were collected bimonthly which was segregated in to pre-monsoon, monsoon and post-monsoon season. For each station the sampling transects were from the shore to 10km into the sea consisting of multiple sampling locations. Water samples from different depths were collected using Niskin water sampler and then transferred to containers for storage in dark ice boxes. SST was measured on site by using Precision thermometer of 0.1ºC accuracy. In laboratory water samples were filtered within 24hr of sampling by using 4.7cm GF/F Whatman filter paper for nitrate analysis. Nitrate analysis was done by following the cadmium reduction method and salinity measurement was carried out by titrimetric method using silver nitrate as titrant. Nitrate and salinity were analysed by following the standard method of Strickland and Parsons, 1972. Chlorophyll-a concentration was measured by using 90% acetone following standard method of (Porra et al.1989).

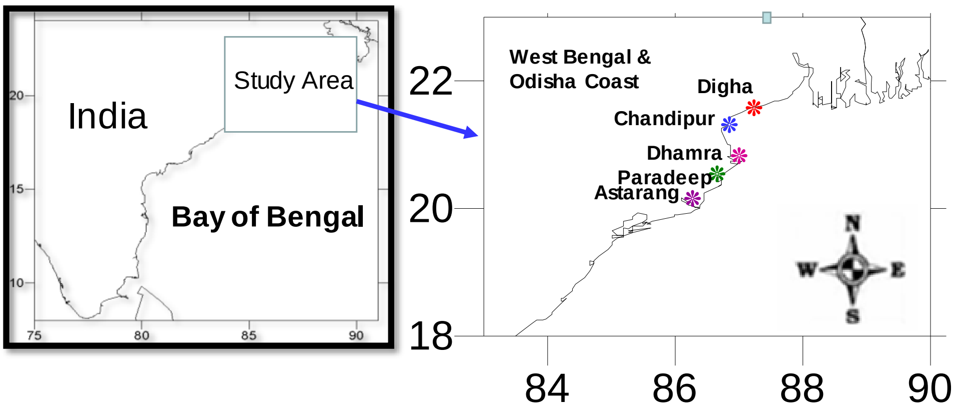

Figure-1 Study area showing the sampling locations along the northwest Bay of Bengal coast

2.3 Processing of satellite data

The nitrate imaging and new production model development requires sea surface temperature and chlorophyll concentration derived from satellite data. The Indian Remote Sensing satellite Oceansat-2 Ocean Color Monitor (OCM) derived chlorophyll data has been acquired from NRSC for the dates during March 2017 over the northwest Bay of Bengal and the NASA MODIS-Aqua Level-2a sea surface temperature and chlorophyll data for the same dates and 8-day data during March 2017 have been acquired from the http://modis.gsfc.nasa.gov. The OCM-2 and MODIS-Aqua chlorophyll algorithms OC-4 and OC-3 respectively used are as follows:

OCM-2 chlorophyll is generated using OC-4 algorithm with necessary fine tuning over Arabian sea cruise datasets (Chauhan et al., 2007) and has been made operational. The algorithm has the following form.

$\log_{10}(\text{Chlorophyll})=(a+b*R+c*R^2+d*R^3)+e$

$R=\log_{10}(Rrs443>Rrs490>Rrs510/Rrs555)$

$a=0.48; b=-3.03; c=2.24; d=-1.25; e=-0.03$

Morel and Maritorena, 2001 have proposed and identified the OC-3 empirical algorithm (also known as Ocean Chlorophyll 3), which has been operated on MODIS-Aqua ocean colour data. The algorithm is incorporating the remote sensing reflectance (R_{rs}) basing on 3 bands 443, 488 and 551 nm for computing chlorophyll concentration C. The algorithm has been used to retrieve low as well as high chlorophyll concentration which means a better retrieval even in case 2 waters. The algorithm operates with five coefficients and has following mathematical form

$C = 10 \wedge ^{(0.283 - 2.753*R + 1.457*R2 - 0.659*R3 - 1.403*R4)}$,

Where $R = \log_{10} [(R_{rs}443>R_{rs}488)/ R_{rs}551]$ and R_{rs} is remote sensing reflectance.

for $0.01 \text{ mg m}^{-3} \leq C \leq 100 \text{ mg m}^{-3}$

In OC-3 algorithm, there should be no negative R_{rs} value, so the greater value is to be considered from the channels R_{rs} 443nm and R_{rs} 488nm as numerator and to be divided by R_{rs} 555nm as denominator.

The data were processed to generate SST and chlorophyll image using ENVI software. The datasets were applied with geometric correction routines to remove the image distortion and bring them to a standard geographic projection (Lat/Lon) with modified Everest Datum.

2.3 Nitrate Retrieval Algorithm

The *in situ* datasets have been regressed to develop nitrate algorithm during the period 2014-2016 (March-June) from monthly sampled coastal water datasets along Odisha and West Bengal coast. The SST and chlorophyll datasets have been regressed with the nitrate three dimensionally using 99 surface water points. Three different functions like linear, Gaussian and paraboloid have been applied for regression analysis (Fig.2) using Sigmaplot software. In overall regression analysis of gaussian function found to be better fit than other functions and producing significant relationship during the pre-monsoon season (R^2=0.61) and derived nitrate algorithm has been used to generate the nitrate images during March 2017.

3.0 Results and discussion

The algorithm for nitrate has been developed for the 1st time in the northwest BoB water along the Odisha and West Bengal coastal water, during pre-monsoon season 2014-2016. The Gaussian function fit showed the best coefficient of determination (R^2) value 0.61 as compared to the linear (0.45) and paraboloid (0.57) 3-dimensional regression fit (Fig. 2). Hence basing on the equation-3 (Fig.2), the nitrate images have been generated for northwest BoB incorporating daily and 8-day SST and chlorophyll images. The chlorophyll, SST and nitrate data ranges and the mean and standard deviation for different dates and 8-days images have been retrieved (Table-1and 2). The Modis-Aqua derived 8-days images chlorophyll and nitrate (>100 µM for about 10 pixels in the image) has been observed very high during the week of 6-13 March 2017. But the daily images have shown the normal trend of chlorophyll and nitrate variability.

There has been observation of high nitrate concentration of the river mouth region of Dhamra coast, NO_3 ranging from 10 to 200µM has been observed in the Modis-aqua derived NO_3 images using chlorophyll and SST datasets. The 8-day time series for the NO_3 has been studied and interpreted during February 26 to March 29, 2017 for four weeks (Fig.3). It shows the coastal water deciphers high (2-10 µM) and very high nitrate (>10 µM) in the coastal water. The northern coastal water of Odisha shows much higher chlorophyll, nitrate concentration as compared to the southern Odisha coastal water. The offshore water shows comparatively low NO_3 conc. (<2 µM). Daily NO_3 images have been derived from the Modis Aqua SST and OCM-2 chlorophyll daily passes. The datasets from different sensors have been made to 1km resolution and the NO_3 images have been generated and interpreted (Fig. 4 and 5). The quantitative variation in the coastal, shelf and offshore water has been observed. The NO3 mostly seen matching with the chlorophyll trend and only in few locations matches with the SST features. Hence the interpretation of NO_3 has been observed to be more close to chlorophyll than SST, during this season.

The validation of nitrate, chlorophyll and SST has been carried out with limited datasets in the shelf and offshore water with the *Sagar Manjusha* ship cruise data during March 20-22, 2017 with the near-synchronous/synchronous satellite data of March 21, 2017. The validation of shells and offshore locations results have been shown in the Table-3. Only the coastal water points have shown reasonably matching nitrate variability from satellite data as compared to in situ data points. As this nitrate algorithm's input data points correspond to only the coastal water regions along Odisha and Bengal coast within 10kilometers distance from the coast. So, more number of in situ data points of coastal water is needed for better validation exercise and accuracy assessment of the algorithm.

There has been difference in the chlorophyll algorithms used for both Modis-Aqua and OCM-2 datasets. The channels used for both the sensor data sets are also different. So, the marginal difference is chlorophyll observation from two different types of sensors using different algorithms is obvious in quantitative match-ups. But the ocean colour features used to be reflected in similar fashion. That is the only advantage using different sensor datasets. Hence the quantitative difference gets observed in imaging the nitrate parameter.

4.0 Conclusion

For the first time, the nitrate algorithm has been developed along the northwest Bay of Bengal coastal water using the *in situ* datasets during pre-monsoon season, March-June 2014-

2016. In total, 99 surface water data points have been used to develop nitrate algorithm with the 3-dimensional regression of SST, chlorophyll and nitrate datasets. The regression was carried out using linear, paraboloid and gaussian function fit incorporating the datasets. The Gaussian function fit depicted the best coefficient of determination value (R^2=0.61) and standard error of estimate (SEE=15.66). This shows deviation in comparison to our earlier work in the southwest Bay of Bengal region work along Tamilnadu coast, where the paraboloid relation has been observed valid in most of the season and in annual scale observations. In the current study the chlorophyll is observed to matching better to nitrate features in comparison with the other input parameter SST, during this season. Probably the upwelling and vertical processes are less and void during the pre-monsoon period, hence the importance of SST in relation to nitrate is not getting reflected in the satellite derived images. The coastal water off Dhamra shows very high concentration of nitrate (20-200 µM) which is unique and is due to the river flux and eutrophic conditions. The northern Odisha and southern Bengal coast, off Digha showed very high nitrate concentration in comparison to southern Odisha coastal water regions and northern Andhra coast. The river flux areas have been the concern of eutrophication during this pre-monsoon season as has been depicted from this current study. The validation results show few matching points as far as the in situ and modelled satellite data is concerned. Hence validation with more number of data points over coastal, shelf and offshore water needed to establish the relation on seasonal and annual scale. Hence modelling, mapping and monitoring of nitrate is needed for the regional ocean phytoplankton and zooplankton productivity and biogeochemical cycles studies.

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Figure and Table captions:

Figure 1. Study area map showing the monthly sampling stations and transect stations in the northwest Bay of Bengal water.

Figure 2. Figure-2 In situ data based modelled nitrate algorithms using the 3-dimensional regressions for (a) linear, (b) paraboloid and (c) gaussian function fits with 99 data points along the Odisha and Bengal coastal water for pre-monsoon season (2014-2016).

Figure-3 MODIS-Aqua 8-day composite SST (a-d), chlorophyll (e-h) and nitrate (i-l) images during March 2017

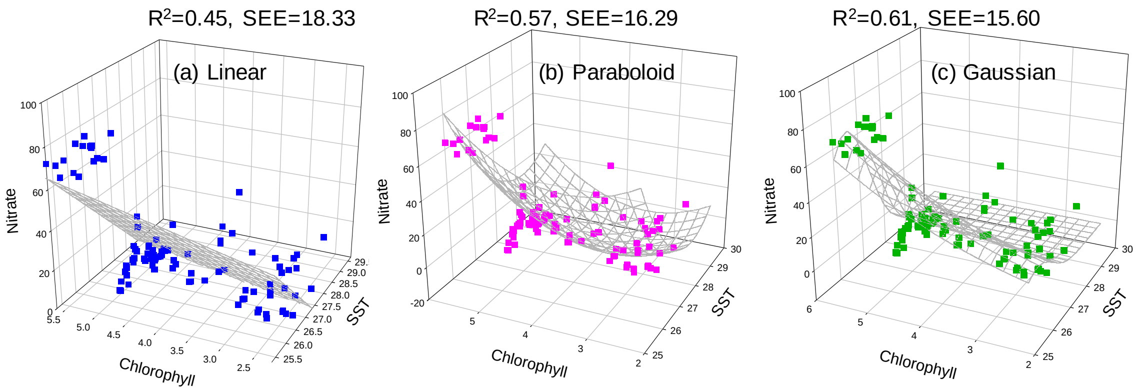
Figure-4 Day-wise nitrate images time series retrieved using daily OCM-2 chlorophyll and MODIS-Aqua SST during March 2017

Figure-5 Day-wise nitrate images displayed along with MODIS-Aqua SST and OCM-2 chlorophyll for two dates during March 2017

Table-1 Modis-Aqua SST and OCM-2 chlorophyll derived daily nitrate during March 2017

Table-2 Weekly (8-days composite) during February 26-March 29, 2017 Modis-Aqua derived chlorophyll, SST and nitrate images value ranges and mean ± standard deviation

Table-3 In situ and satellite derived Chlorophyll, SST and nitrate data points



$$\text{(a) } NO_3 = 543.134 - 20.417*SST + 6.925*Chl \text{ --------------- (1)}$$

$$\text{(b) } NO_3 = 5404.74 - 373.953*SST - 49.62*Chl + 6.561*SST^2 + 7.093*Chl^2 \text{ -------- (2)}$$

$$\text{(c) } NO_3 = 507.2* e^{(-0.5*(((SST-25.797)/0.838)^{\wedge}2 + ((Chl-16.983)/5.78)^{\wedge}2))} \text{ -------------- (3)}$$

Figure-2 In situ data based modelled nitrate algorithms using the 3-dimensional regressions for (a) linear, (b) paraboloid and (c) gaussian function fits with 99 data points along the Odisha and Bengal coastal water for pre-monsoon season(2014-2016).

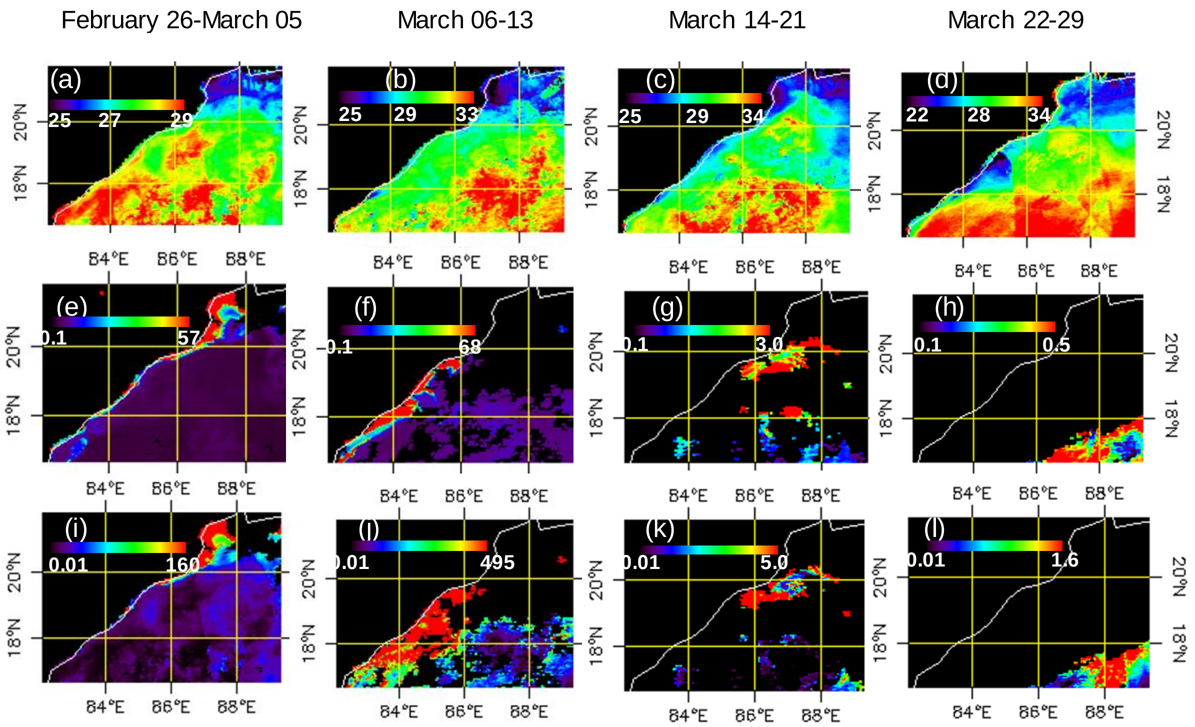


Figure-3 MODIS-Aqua 8-day composite SST (a-d), chlorophyll (e-h) and nitrate (i-l) images during March 2017.

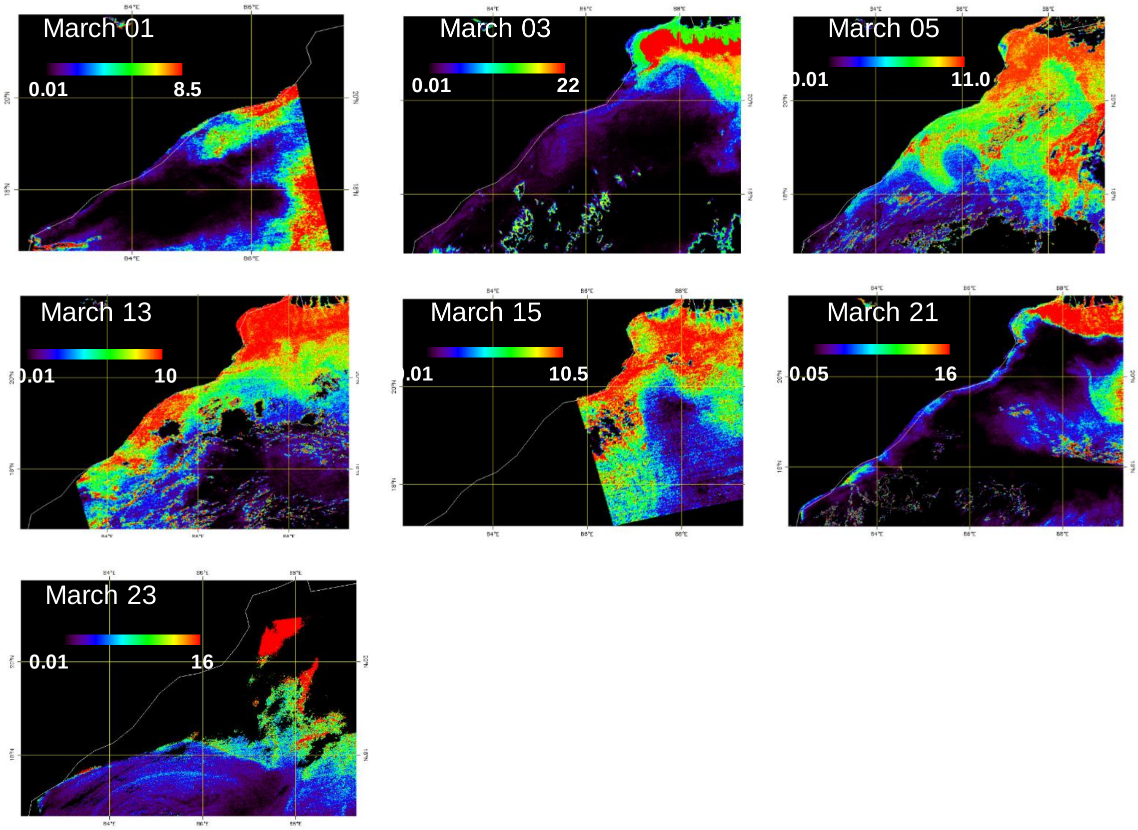


Figure-4 Day-wise nitrate images retrieved using daily OCM-2 chlorophyll and MODIS-Aqua SST during March 2017.

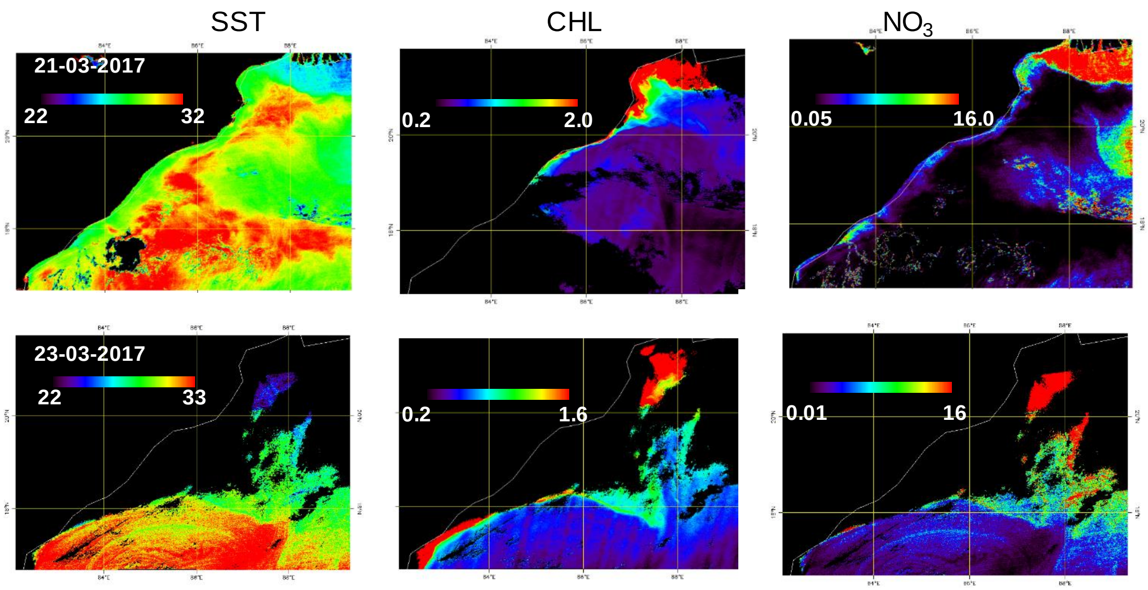


Figure-5 Day-wise nitrate images displayed along with MODIS-Aqua SST and OCM-2 chlorophyll for two dates during March 2017.

Table-1 Modis-Aqua SST and OCM-2 chlorophyll derived daily nitrate during March 2017

daily data NO_3	**Minimum**	**Maximum**	**Mean ± SD**
01-03-2017	0.01	8.39	1.50 ± 1.86
03-03-2017	0.01	**22.08**	1.61 ± 3.06
05-03-2017	0.01	10.85	3.62 ± 2.29
13-03-2017	0.009	9.86	2.82 ± 2.44
15-03-2017	0.01	10.29	3.68 ±2.10
21-03-2017	0.06	**15.94**	1.10 ± 2.12
23-03-2017	0.01	**15.93**	0.78 ±1.13

Table-2 Weekly (8-days composite) during February 26-March 29, 2017 Modis-Aqua derived chlorophyll, SST and nitrate images value ranges and mean ± standard deviation

Parameters	**Dates**	**Minimum**	**Maximum**	**Mean ± SD**
SST	26feb-5th March	25.2	**28.76**	27.20 ± 0.50
Chlorophyll	26feb-5th March	0.11	**57.05**	0.47 ± 1.58
NO_3	26feb-5th March	0.04	**160.42**	3.35 ± 9.36
SST	6th-13th March	25.36	**33.75**	27.25 ± 0.57
Chlorophyll	6th-13th March	0.10	**68.60**	1.30 ± 5.43
NO_3	6th -13th March	0.01	**495.2**	5.43 ± 27.42
SST	14th-21st March	25.63	34.0	27.73 ± 0.72
Chlorophyll	14th-21st March	0.10	2.32	0.25 ± 0.19
NO_3	14th -21st March	0.01	4.38	0.4 ± 0.55
SST	22nd-29th March	22.25	34.0	27.22 ± 0.58
Chlorophyll	22nd-29th March	0.10	0.25	0.13 ± 0.01
NO_3	22nd–29th March	0.02	1.51	0.58 ± 0.31

Table-3 In situ and satellite derived Chlorophyll, SST and nitrate data points

March 2017 Cruise Stations	*In situ* chl (Date and time)	OCM-2 Chl **March 21, 2017 12:00Hrs**	*In situ* SST	Modis SST	*In situ* NO_3	Satellite NO_3
Gopalpur-1 **(10km from coast)**	**2.24 (March 20, 10Hrs)**	**0.44**	27.98	26.8	**6.39**	**3.29**
Gopalpur-2 (20 km from coast)	2.63 (March 20, 11:30Hrs)	0.62	28.04	28	4.29	0.24
Gopalpur-4 (40 km from coast)	2.94 (March 20, 15:00Hrs)	0.59	27.62	28.04	4.41	0.2
Ganjam-1 **(10km from coast)**	**1.98 (March 21, 10Hrs)**	**0.74**	28.2	27.35	**6.95**	**1.78**
Ganjam-3 (30km from coast)	1.64 (March 21, 13:00Hrs)	0.56	28.98	27.56	4.41	1.02
Chilika-2 (20km from coast)	2.64 (March 22, 11:30 Hrs)	0.53	28.48	27.6	7.88	0.9