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Seasonal algal bloom and water quality around the coastal Kerala during southwest monsoon using *in situ* and satellite data

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Algal bloom has been observed using IRS-P4 (Oceansat-1) OCM data and *in situ* observations during September 2002 and 2003 around the Kerala coastal and shelf water off Calicut. Algal bloom features have been observed in the total radiance, remote sensing reflectance, chlorophyll and diffuse attenuation coefficient images. *In situ* observations indicated the dominance of dinoflagellate *Noctiluca scintillensis* in the 1st, 2nd and 3rd weeks of September 2002. Red colour of water was seen even upto 30-35 kilometer from coastline and this has been got reflected in OCM derived chlorophyll images with the dense algal bloom features with very high chlorophyll concentration (20-50 mg/m^3). During September (8, 20, 22, 24 and 30) 2003, high dense algal bloom patches (chl>20 mg/m^3) were seen around the Calicut coast in the OCM images and spreads across the Kerala coast in the shelf water up to 20-30 km from coastline. Water colour has been found even green due to toxic micro algae *Hornelia marina*. Water quality parameters like SST, dissolved oxygen, salinity, pH, productivity and nutrients have been correlated with the bloom phenomenon.

[Keywords: Algal bloom, Kerala coast, water quality parameters, *in situ*, satellite data]

Introduction

Remote Sensing of ocean colour yields information on the constituents of Sea water, such as the concentration of phytoplankton pigments, suspended sediments and yellow substance. Satellites data can provide wide-ranging, often repeated coverage of some properties, like the chlorophyll content of the upper parts of the euphotic zone[1]. Methods of detecting and mapping seawater constituents from aircraft and from space-borne platform have been successfully developed during the past three decades[2-4]. Satellite measurements has been applied successfully to the measurements and mapping of surface pigment concentrations[5-7]. Satellite observations of ocean colour provide large-scale, repeat coverage sampling of global ocean chlorophyll that are necessary to help understand the role of phytoplankton on biogeochemical cycling, climate change and fisheries[8].

Arabian Sea is a region, where the monsoon wind forcing plays a major role and the biological production is affected by the physical processes altering the vertical flux of nutrients in the mixed layer[9]. Satellite based observations on ocean color provides a tool to monitor the biological productivity in term of phytoplankton concentration. Occasionally phytoplankton grows very fast or “blooms” and accumulates into dense, visible patches near the surface water. The blooms can form rapidly and it is often difficult to assess their development and extent from traditional sampling methods using a boat or a fixed-site monitoring station. Remote sensing technique offers a practical tool in overcoming these problems[10-11].

Large areas can be covered rapidly to determine the spatial extent of a bloom in near real time by remote sensing method, providing quick and effective means to detect and monitor bloom formation[12]. Satellite detection and monitoring of harmful algal blooms (HABs) require methods/algorithms that have been developed mostly based on extensive *in-situ* bio-optical observations from optically less complex oceanic waters and optical modeling of water properties[13]. Massive blooms of cyanobacteria attract the attention of environmental agencies, water authorities, and human and animal health organizations since cyanobacteria can cause a range of amenity, water quality and treatment problems, human and animal helath hazards[14]. It has been

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shown[15] that the spatial and temporal frequencies of the conventional water sampling programs are not adequate to report changes in phytoplankton biomass, especially during bloom conditions when the variability in the phytoplankton density is particularly high. The use of unattended flow-through systems on ship-of-opportunity[15], airborne[16] and satellite remote sensing[17-19] have been recommended to acquire more reliable information about the extent of cyanobacterial blooms than the conventional monitoring programs can provide. In the present study, a massive algal bloom has been detected using *in situ* and IRS-P4 OCM data around the Kerala coast and water leaving radiance images have been inter-compared.

Ocean colour monitor (OCM) of the Indian Remote Sensing satellite IRS-P4 is optimally designed for the estimation of chlorophyll in coastal and oceanic waters, detection and monitoring of phytoplankton blooms, studying the suspended sediment dynamics and the characterization of the atmospheric aerosols. The technical specifications of the OCM sensor are given in Table 1. In the present study, the algal blooming has been monitored in the chlorophyll images derived from the IRS-P4 OCM data around the southeast Arabian Sea and the movement mechanism of blooming features (algal filaments) are discussed during the period September 2002 and 2003.

Materials and Methods

In situ water quality parameters data has been collected by CMFRI, Cochin including the chlorophyll, productivity, nutrients, dissolved oxygen, salinity, temperature and other parameters. The retrieval of ocean colour parameter such as phytoplankton pigment (chlorophyll-a) in oceanic waters, involves two major steps, the atmospheric correction of visible channels to obtain normalized water leaving radiances in shorter wavelengths and application of the bio-optical algorithm for retrieval of phytoplankton pigment concentrations.

Table 1—Technical characteristics of IRS P4 OCM payload

Spectral Range	404-882 nm
No. of channels	8
Wavelengths range (nm) and Signal to noise ratio (SNR)	Channel 1:404-423 (340.5) Channel 2:431-451 (440.7) Channel 3:475-495 (427.6) Channel 4:501-520 (408.8) Channel 5:547-565 (412.2) Channel 6:660-677 (345.6) Channel 7:749-787 (393.7) Channel 8:847-882 (253.6)
Satellite altitude (km)	720
Spatial resolution (m)	360×236
Swath (km)	1420
Repeativity	2 days
Quantisation	12 bits
Equatorial crossing time	12 noon
Along track steering (to avoid sunglint)	20°

Atmospheric correction of the IRS-P4 OCM imagery

In remote sensing of the ocean, the signal received at the satellite altitude is dominated by radiance contributions through atmospheric scattering processes and only 8-10% signal corresponds to oceanic reflectance[20]. Therefore it has been mandatory to correct the atmospheric effect to retrieve any quantitative parameter from space. An algorithm has been developed at Space Applications Centre (ISRO), Ahmedabad, to correct OCM data for atmospheric contamination[21]. The OCM scenes were corrected for atmospheric effects of Rayleigh and aerosol scattering using an approach called long wavelength atmospheric correction method. The approach used the two near-infrared channels at 765 and 865 nm to correct for the contribution of molecular and aerosol scattering in visible wavelengths at 412, 443, 490, 510, and 555 nm[20]. The water leaving radiances derived after atmospheric correction is converted to remote sensing reflectance (R_{rs}) using the following formula and were used to compute chlorophyll-a pigment concentration.

$$R_{rs} = \pi L_w / F_0,$$

where L_w is the water leaving radiance and F_0 is the extra-terrestrial solar flux.

Chlorophyll algorithm

A number of bio-optical algorithm for retrieval of chlorophyll have been developed to relate measurements of water leaving radiance to the *in situ* concentrations of phytoplankton pigments. An empirical algorithm (also known as Ocean Chlorophyll 2 or OC2) is being operated for SeaWiFS ocean colour data[22]. This algorithm captures the inherent sigmoid relationship between the log transformed band ratio ($R_{rs}490/R_{rs}555$) and chlorophyll concentration C, where R_{rs} is the remote sensing reflectance at 490 and 555 nm bands respectively. The algorithm was shown to retrieve low as well as high chlorophyll concentration which means a better retrieval even in case 2 waters[21]. The algorithm operates with five coefficients and has the following mathematical form.

$$C = -0.040 + 10^{[0.32 - 2.33 * X + 0.87 * X2 - 0.14* X3]}$$

where C is chlorophyll concentration in mg/m^3 and $X = \log_{10}[R_{rs}490/ R_{rs}555]$.

While comparing all available algorithms for Indian waters, it was observed that this algorithm provided best results for chlorophyll retrieval[23]. This algorithm has been presently used for generating the chlorophyll maps, using IRS-P4 OCM derived water leaving radiances.

Diffuse attenuation coefficient (K_d)

The vertical downwelling diffuse attenuation coefficient, K_d is an apparent optical property since its magnitude depends on the irradiance distribution at the time and point of measurement[24].

The diffuse attenuation coefficient K_d for any wavelength or spectral band is defined as

$$K_d = 1/E (z) * dE(z)/dz$$

where E is the irradiance energy and z is the depth. The diffuse attenuation coefficient algorithm for determining the downwelling irradiance coefficient, or K, for case 1 waters used the upwelling radiance from the 443nm and 550nm bands[25,26]. The algorithm for K at 490nm has the following form

$$K_d (490) = 0.124*[L_{wn}(443) / L_{wn}(555)]^{-1.64} + 0.022$$

Where, $L_{wn}(443)$ and $L_{wn}(550)$ are the normalized water leaving radiances in the 443 and 550 nm channels, respectively.

Dataset Used

In situ data of water quality parameters have been collected around the Kerala coast from the Central Marine Fishery Research Institute (CMFRI), Calicut field survey program during September 2002 and 2003. The chlorophyll-a, radiance, water leaving reflectance and diffuse attenuation coefficient K_d (490) map was generated using the above mentioned procedure from the IRS-P4 OCM (Path 10 and Row 14 and data during September 2002 and 2003 around Kerala coastal water (Figs. 1,2). The data in bloom water from the total radiance, water leaving radiance, chlorophyll and Kd images have been plotted (Figs. 3,4).

Results and Discussion

Algal bloom has been observed using IRS-P4 (Oceansat-1) OCM data and *in situ* observations during September 2002 and 2003 around the Kerala coastal and shelf water of Calicut. The algal bloom features have been observed in the total radiance, remote sensing reflectance, chlorophyll and diffuse attenuation coefficient images. The study has been carried out with less-cloudy OCM passes during September 2002 (dates 1, 3, 13, 15, 19, 23 and 27) and September 2003 (dates 18, 20, 22, 24, 28 and 30). *In situ* observations indicate the dominance of dinoflagellate *Noctiluca scintillensis* in the 1st, 2nd and 3rd weeks of September 2002. In the south of Calicut coast, mass mortality of fishes have been observed, it possibly point out the harmful impact of algal bloom diminishing the food chain. Water colour has been found green due to toxic micro algae *Hornelia marina (Green tide)*. The bloom extended up to 22nd September. The discoloration was found to be due to algal bloom. Massive death of green mussel, *Perna viridis* has been seen during September 2002, 3rd week around Calicut. The bloom has been reported in the coastal water of Calicut and Kannur. Even big fishes like eel have been washed ashore. The fishes perished due to lack of oxygen in water column due to algal bloom. In latter stage water even turned red colour in the bloom water. The fishermen reported the red coloration of water even upto 30-35 kilometer from coastline and this has got reflected in OCM derived chlorophyll images with the dense algal bloom features[4]. The red colour of water was due to the dinoflagellate *Noctiluca scintillensis*, caused red tide with very high chlorophyll concentration (20-50 mg/m^3). The oxygen deficiency due to the swarming of *Noctiluca scintillensis* led to the mortality of fishes and marine fauna. The water currents have moved dense blooms towards offshore and near coast. The Second algal bloom occurred on 14th and 15th of September along the coast of Kozhikode South upto Puthiappa Harbour, 8 km along the coast. Mass mortality of small fishes to fish weighing upto 10 kg noticed along the coast. It was found that water turned green in colour due to the presence of micro algae *Hornellia marina* and used to refer as GREEN TIDES. Fishes like *Epinephellis malabaricus*, *Otolithes argenteus*, *Kowala coval*, *Anchovila heterobus Nemipterus japonicus* and *Mugil speilleri* etc. have been found as part of mass mortality.

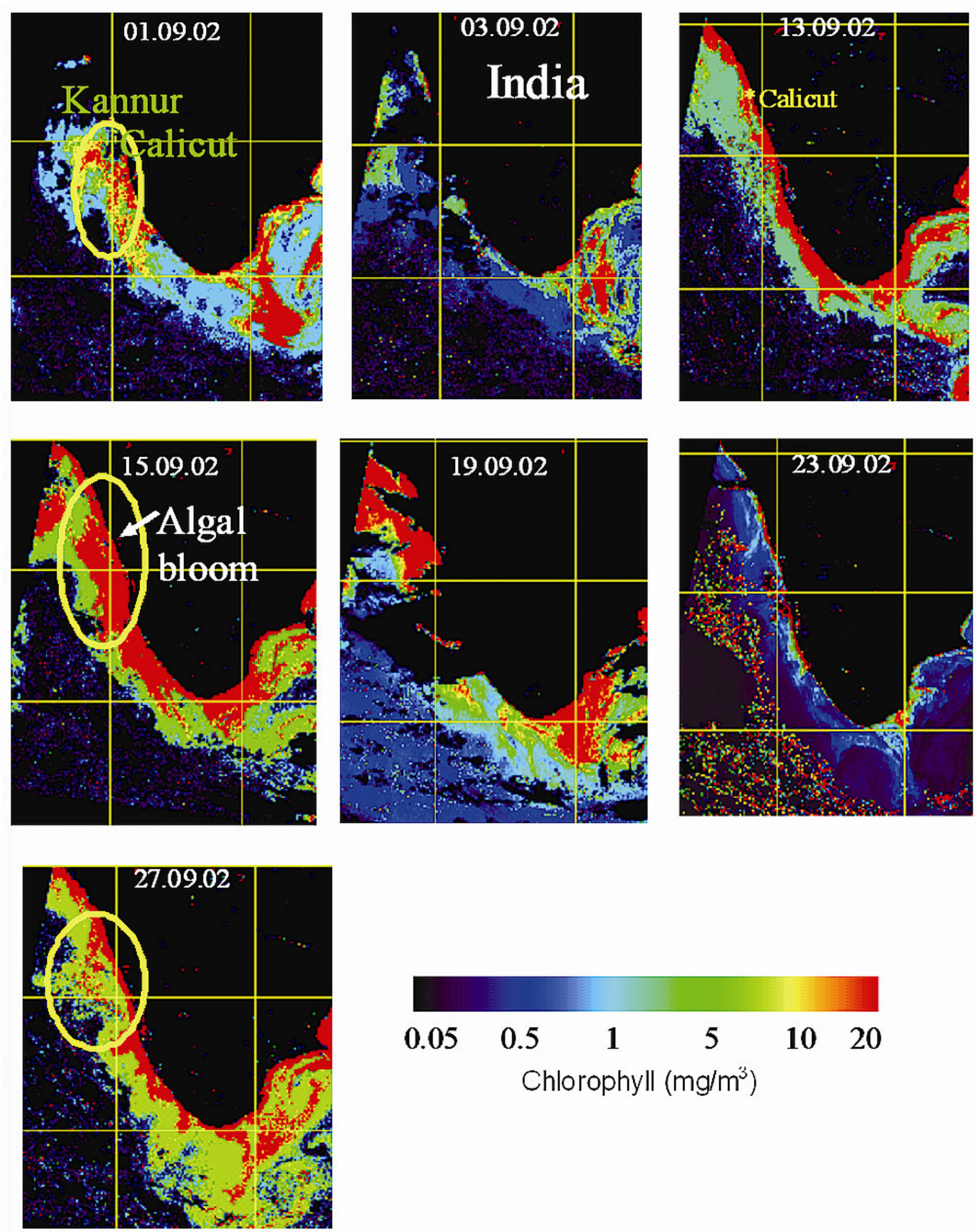

Fig. 1—IRS-P4 OCM derived chlorophyll images during the algal bloom phases in September 2002 around the Kerala coast.

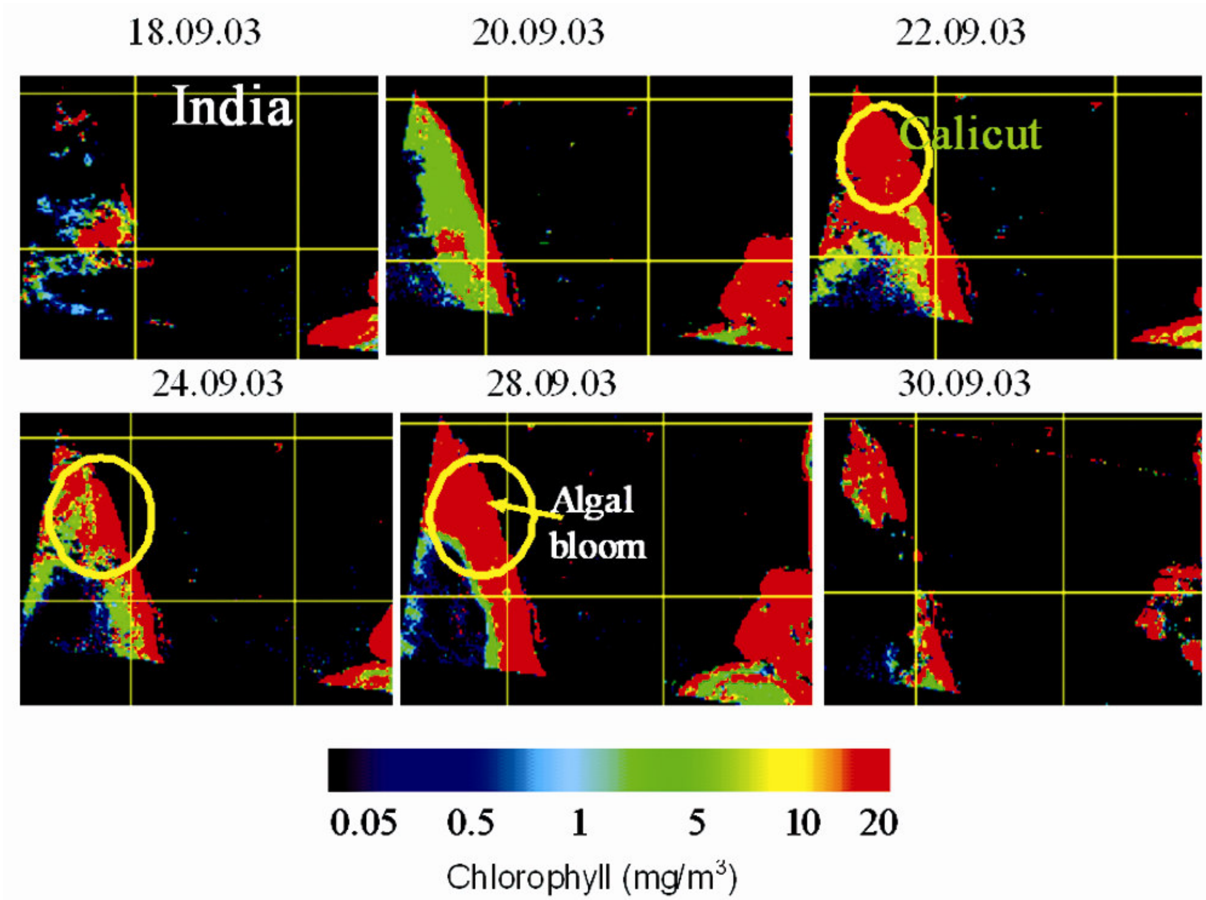

Fig. 2—IRS-P4 OCM derived chlorophyll images during the algal bloom phases in September 2003 around the Kerala coast.

During September 2002, three blooms of high intensity were recorded. The successive blooms may be attributed to the delayed southwest monsoon and intermittent showers followed by bright sunshine. Additional features which onset the bloom are upwelling which continues till November and enrichment of coastal water due to the flushing of monsoonal rain. The oxygen concentration around Calicut ranged 0.96-1.67 mL/L, which was much below normal range 4-5 mL/L. There has been observation of decrease in water temperature range. It was 22.4-26°C than the normal range 28-30°C. Low temperature of water is the indication of upwelling. pH ranged from 7.21-7.57. Nutrients such as nitrate, nitrite and phosphate values recorded high during the algal bloom period. The intensity of bloom in 2003 September was less compared to the bloom of 2002 September. The bloom was noticed in the 3rd week of September in the coastal water around Calicut, but the death of fishes and mussels were not noticed. The green micro algae *Hornelia marina* bloom has been observed around Calicut on 22 September 2003. There has been observation of very high gross primary productivity (13.104 gC/m^3/day), SST ~27.5°C, salinity ~35.07 ppt, pH ~7.37 and DO ~3.46 mL/L (Tables - 2,3,4). There has been observation of decrease in dissolved oxygen (~3.85 ml/L), decrease in SST (25.5°C), increase in phosphate (0.171 µg atm/L) and nitrate (0.085 µg atm/L) during September 2003 from monthly trend data (April-September) (Tables - 2,3,4). During September 2002, the *in situ* chlorophyll concentration was around 10-30 mg/m^3 and OCM derived chlorophyll ranged around 20-50 mg/m^3 for the dates 13, 15, 19 and 27 September 2002. During September 2003, dates 8, 20, 22, 24 and 30 indicate the high dense algal bloom patches (chl>20 mg/m^3) around the Calicut coast in the OCM images. This indicates seasonal algal bloom around the Calicut coast, which spreads across the Kerala coast in the shelf water up to 20-30 km from coastline. Striking amounts of mucus accompany some blooms of *Chattonella spp.* recognized as *Hornellia marina/Chattonella marina*[27] was first described

Table 2—Hydrography of bloom waters at Calicut on 22.09.2003

Date	Temp. ºC	Salinity. ppt	Dissolved Oxygen Ml/L	pH	Gross Productivity gC/m^3/day
22.09.2003	27.5	35.07	3.46	7.37	13.104

Table 3—Hydrography of bloom waters at Calicut on 24.09.2003

Station	Temp. ºC	Salin ppt	Diss. Oxyg. Ml/L	pH	Phos. µg.at /L	Nitrite µg.at /L	Nitrate µg.at /L	Gross Producti. gC/m^3/day
South Beach	24.0	35.41	4.04	7.35	0.050	0.004	0.012	4.048
Port office Beach	24.5	35.27	3.84	7.32	0.087	0.003	0.012	4.288
Varackal Beach	24.5	35.13	1.73	6.98	0.248	0.008	0.010	3.962
Koya road Beach	24.5	35.69	2.21	6.98	0.370	0.025	0.025	1.818
Puthiappa Harbour	23.0	35.41	1.44	7.08	0.103	0.001	0.003	3.945

Table 4—Hydrography of normal waters of Calicut during six months April to September 2003

Month & Year	Temp. ºC	Salin ppt	Diss. oxy Ml/L	pH	Phos. µg.at/L	Nitrite µg.at/L	Nitrate µg.at/L	Gross Production gC/m^3/d	Rainfall (mm)
2003									
April	30.5	34.59	3.27	7.5	0.040	0.023	0.003	2.491	199
May	29.7	34.91	3.78	7.5	0.050	0.029	0.003	2.590	90
June	28.4	33.78	4.24	7.5	0.058	0.046	0.014	2.744	921
July	25.8	32.54	4.16	7.6	0.054	0.002	0.079	0.545	516
Aug.	24.7	33.01	4.30	7.5	0.070	0.002	0.110	1.342	230
Sep.	25.5	33.53	3.85	7.4	0.171	0.010	0.085	1.038	164

from viscous, slimy blooms causing huge kills of wild fish around Malabar coast. The micro algae belong to the class Raphidophyceae. Several different toxic components produced, causing mortality of fish, gill damage and decrease in heart rate of fish caused by brevetoxins, resulting in reduced flow of oxygen to the gills. Fish, shrimp and crab mortality have been reported earlier.

The OCM reflectance images indicate high reflectance (1-2%) in extreme blue and green channels; 490, 512 and 555 nm of OCM respectively. So, this might be due to the reflectance of green algae *Hornelia marina*, which causes green tide, even the dinoflagellate *Noctiluca* bloom indicates high chlorophyll value. Even during September 2003, the OCM reflectance was highest in channel 5 (550 nm) of OCM on 20th September, followed by channel 3 and 4, 490 and 512 nm (0.5-1.5%) during 22-30th September 2003 around Calicut coast bloom water (Fig. 3). The green tide due to micro algae *Hornelia marina* might be playing a leading role in addition to dinoflagellate *Noctiluca scintillensis*. Detailed *in situ* observation with radiometer would provide vital information. The attenuation coefficient (Kd) hasn’t shown much variation during 2002 September in the bloom region with low range 0.15-0.20 m^{-1}. It shows the weather was sunshiny with better transparency. But, during September 2003, Kd indicated variation and was high ranging 0.7-0.85 m^{-1} (Fig. 4). It indicated high Kd value and low transparency of water, partially cloudy weather resulting in algal bloom with high chlorophyll concentration. The *in situ* observed algal bloom around Calicut during September 2002 and 2003 has been well reflected in the respective date OCM observed chlorophyll images with dense chlorophyll patches and stripes along the coast. The chlorophyll concentration from *in situ* data matches well with OCM derived chlorophyll. During bloom the chlorophyll ranged around 20-30 mg/m^3 from the *in situ* and satellite data (Fig. 4).

Coastal upwelling is a consequence of the alongshore wind stress component all year round along this coast with the monthly mean alongshore wind stress component directed toward the equator[28]. Upwelling is an important process in redistribution of nutrients in the oceanic regime. It causes profound increase in productivity of a region by increasing nutrient content in the euphotic zone. In the process, the cooler nutrient-rich waters from beneath are drawn upwards when strong winds push the warm surface waters away from shore. The plant life,

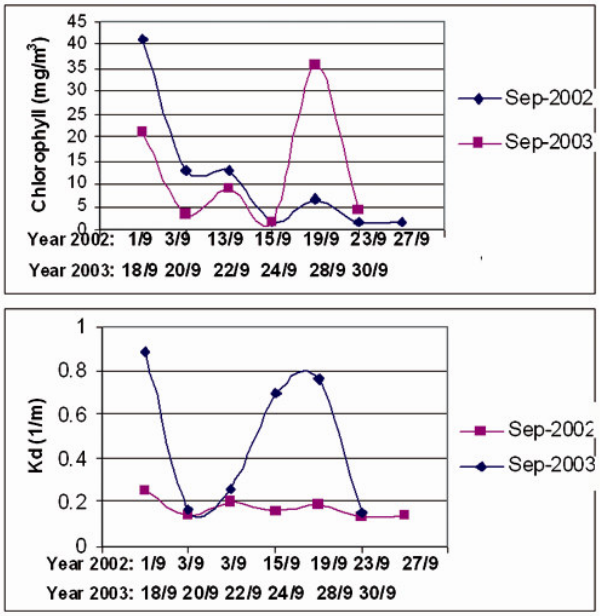

Fig. 3(a,b)—OCM pass dates indication Kd and chlorophyll in the algal bloom laden water around Calicut coast, Kerala compared with the observations and water quality parameters data from CMFRI.

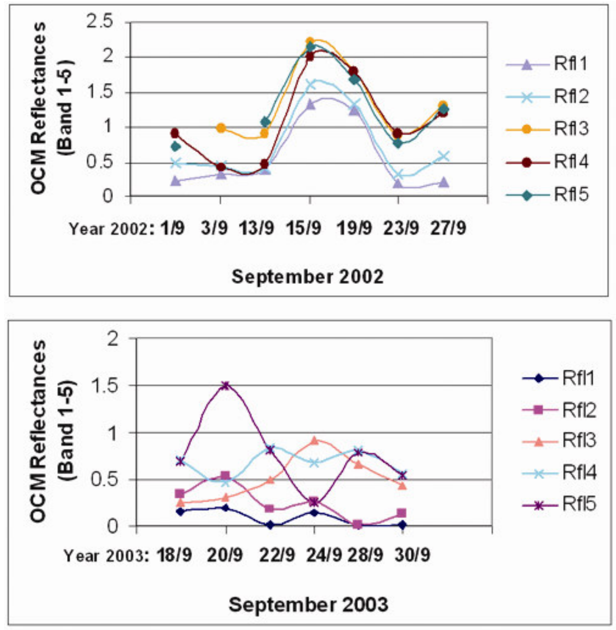

Fig. 4(a,b)—Remote sensing reflectance observed different OCM channels to study the variations during september 2002 and 2003 on different dates with reference to the algal bloom near Calicut coast.

particularly plankton, thrives here and not surprisingly such areas are associated with active fishery[29] and also regular occurrence of algal blooms. The coastal areas of Arabian Sea are major upwelling zones during southwest monsoon[30]. The Arabian Sea shows maximum abundance of phytoplankton and zooplankton[31]. A strong upwelling is regularly observed here during summer[32] and the whole of southwest monsoon season, largely restricted to the shelf[33]. In fact, hydrographic data suggest that the upwelling starts in March and continues till September along the Kerala coast[34]. The current study is a good example of the upwelling induced algal bloom citing both toxic and non-toxic impact causing the green tide and red tide respectively by *Hornelia* and *Noctiluca* phytoplankters.

Inter annual observations needed in the study area and methods can be applied to stop this mass mortality of fishes and damage in the local food chain and food web. Harmful Algal Blooms (HABs) are of national concern because they adversely affect not only the health of people and marine organisms, but also the "health" of local and regional economies. Health effects range from cell damage to organism mortality through such mechanisms as toxin production and localized conditions of low oxygen and even cause casualties in human beings due to transfer of toxins in food chain. Most harmful algal blooms are caused by *plants* that form the "base" of the food chain. These include the microscopic species of algae, the phytoplankton. A bloom occurs when an algae rapidly increases in numbers to the extent that it dominates the local planktonic or benthic community. Such high abundance result to explosive growth, caused for example, by a metabolic response to a particular stimulus such as nutrients or some environmental condition like a change in water temperature or from the physical concentration of a species in a certain area due to local patterns in water circulation. These factors need to be concentrated and to be studied thoroughly. In fact there has been observation of decrease in SST (25.5°C), increase in phosphate (0.171 µg atm/L) and nitrate (0.085 µg atm/L) from monthly trend data. The spectral characteristics with respect to *in situ* radiometers and satellite hyper-spectral channels will be an important study for future. The *in situ* observations basing on the measured water quality parameters and optical properties will be of interest from remote sensing based bio-optical algorithms and biodiversity study.

In the present study algal bloom due to the dinoflagellate *Noctiluca scintillensis* (red tide) and toxic micro algae, *Hornelia marina* (green tide) has been observed and monitored around Calicut, Kerala coast, during September 2002 and 2003. There has been observation of very high gross primary productivity (13.104 gC/m^3/day), SST ~27.5°C, salinity ~35.07 ppt, pH ~7.37 and DO ~3.46 ml/L. There has been observation of decrease in dissolved oxygen (~3.85 mL/L), decrease in SST (25.5°C), increase in phosphate (0.171 µg atm/L) and nitrate (0.085 µg atm/L) from monthly trend data. There has been observation of increase in chlorophyll concentration in the bloom water, which was peaking up to 20-30 mg/m^3 around Calicut coast, which is reflected in IRS-P4 OCM satellite derived images. During September 2003, Kd indicated variation and was high ranging 0.7-0.85 m^{-1}. It indicated high Kd value and low transparency of water, partially cloudy weather resulting in algal bloom with high chlorophyll concentration. The OCM reflectance images indicated high reflectance (1-2%) in extreme blue and green channels; 490, 512 and 555 nm of OCM respectively. So, this indicated due to the reflectance of green algae *Hornelia marina*, which causes green tide, even the dinoflagellate *Noctiluca* bloom indicates high chlorophyll value. Inter annual observations needed in the study area and methods can be applied to stop this mass mortality of fishes and damage in the local food chain and food web due to HABs. *Noctiluca scintilensis* is a bioluminescent algae, the bioluminescence can be monitored with high intensity bloom during night time. The spectral characteristics of *Noctiluca* with respect to *in situ* radiometers and satellite hyper-spectral channels will be an important study for future. Significant attempt needs to be made to develop algorithms for the red tide and green tides in the observed water.

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