



RESEARCH ARTICLE

Hyperspectral Radiometric Observation of the Northeast Arabians Sea during April 2006

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Abstract Parameters were retrieved from the hyperspectral radiometer like upwelling and downwelling radiance (Lu and Ed) upwelling and downwelling attenuation (K-Lu and K-Ed) for 9 stations in the northeast Arabian Sea between 16–26 April 2006. Data was analyzed for 5 offshore and

4 coastal stations of the cruise SS-244, on board FORV “Sagar Sampada” between latitude 9–22°N and longitude 68–74° E. The peak for all parameters was observed to be different respectively for depths 1, 5, 10, 20, 30, 40, 50 meters in coastal and offshore stations. Each peak in the respective wavelength is due to a particular composition; phytoplankton pigments have spectral peaks at 443, 490, 555, 670 nm, suspended matter, sediments have peaks at 630 and 670 nm. Detailed analysis with High Performance Liquid Chromatography (HPLC) data and comparison with the water composition of our hyperspectral radiometer results show that the marine cyanophyte, *Trichodesmium* bloom produces high pigment concentrations of chlorophyll-a, zeaxanthin, β -carotene and pheophytin and their absorptions are interpreted at wavelengths 443, 490, 515 and 536 nanometers, respectively. A dip around 515 nm was seen in the Ed and Lu profiles in our study.

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Introduction

Recent advances in hydrologic optics offer potential for quantitative maps of the inherent optical properties, which can be inverted into optically significant constituents (Aarup *et al.*, 1996). Robust estimates for phytoplankton community composition could be achieved but required constraints on the inversion that phytoplankton dominate the red light absorption (Mobley, 1994). The best profile datasets having tilt angle less than 20° during our cruise measurements have been accounted for study and have been plotted versus depth. Algorithms have been developed to relate remotely sensed parameters to in-water constituents including chlorophyll concentration and water constituents (Chang *et al.*, 2003). It is suggested that traditional water mass markers might be complimented with standard biological measurements such as chlorophyll as an additional dimension would improve resolving water types in parameter space (Tomczak, 1999). Most of the coastal systems reflect the optical contributions of numerous in-water constituents—water, phytoplankton, CDOM, detritus and sediment (Mobley, 1994).

In this study, we have assessed the application of hyperspectral radiometer data for different depths. The optical response in different channels are responsible for the constituents of the water in surface and depths of water column, based on coastal and offshore locations. *In situ* radiometric measurements data were collected in the northeast Arabian Sea comprising 9 stations (5 offshore and 4 coastal) off the Indian west coast. Spectral measurements were carried out in the study area using Hobilabs, Hyperspectral radiometer covering the spectral range between wavelengths (300–900 nm). Very few studies have been done in the context of spectral properties, characteristics of the various ocean pigments and their relationship to algal blooming conditions, especially in the Indian Ocean. This is a preliminary investigation to infer the spectral responses of the water column observed during the cruise on board “Sagar Sampada” between 15–29 April, 2006 in the northeast Arabian Sea, along the Indian west coast. Earlier, survey and study have been carried out us-

ing LICOR and Satlantic underwater radiometers in the Indian waters (Sarangi *et al.*, 2002; Pradhan *et al.*, 2005; Mishra and Rao, 2002; Chauhan *et al.*, 2002a, 2002b and Menon *et al.*, 2005). The current hyperspectral underwater radiometer procured from Hobilabs Inc., USA was operated for the first time in the Arabian Sea and significant observations have been reflected.

Objectives

As a part of the hyperspectral measurements, this study has the following objectives:

- (1) Compare and interpret the *in situ* spectral measurements like upwelling radiance (Lu) and downwelling irradiance (Ed), attenuated upwelling radiance (KLu) and attenuated downwelling irradiance (KEd) and Photosynthetically Active Radiation (PAR) in different depths and at coastal/offshore stations for understanding the optical property.
- (2) To compare the *in situ* measured Lu, Ed, KLu, KEd and PAR with the High Performance Liquid Chromatography (HPLC) derived various pigments in the water column to understand and link the various spectral peaks in the surface and sub-surface depths (5,10,20,30,40,50 meters) of water column with respect to light penetration.
- (3) To investigate the bloom conditions, *Trichodesmium* density/concentration and responsible pigments with respect to their spectral/radiometric behavior.

Study area and methodology

The northeastern Arabian Sea covering offshore and coastal waters from Cochin to Okha in the range 9° – 22° N and 68° – 74° E co-ordinates were selected as the study area for sea truth data collection (Table 1). Distribution of stations for data collection covered coastal and offshore water. Station locations and

cruise track are delineated in Fig. 1. At each station, water sample was collected with Niskin bottles from surface and at depths mentioned earlier, in water column. Aliquots were filtered, under low vacuum (<10 cm Hg), through GF/F (Whatman) glass filters

to concentrate the particles for pigments determination. Filters were placed into snap top vial and quickly frozen in liquid nitrogen. Samples were stored at -80°C until later analysis. Filters were analyzed for photosynthetic and photo protective pigments were determined using high-performance liquid chromatography (HPLC) according to procedures of Wright *et al.*, 1991.

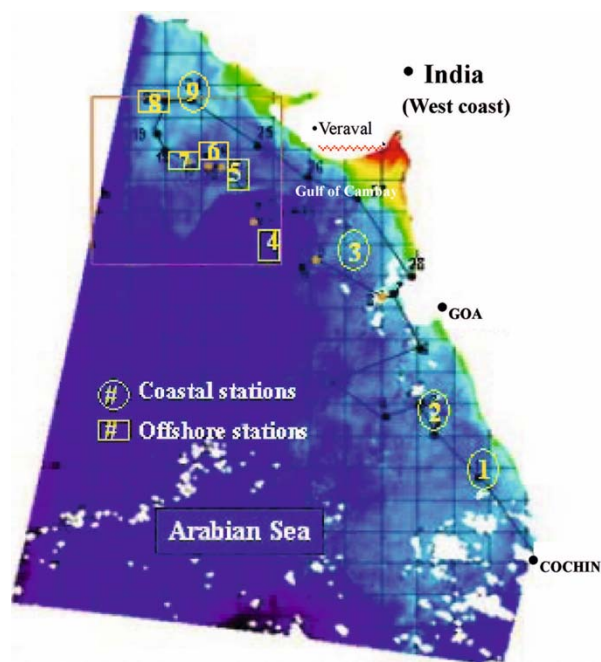


Fig. 1 Study area with station locations have been superimposed on the IRS-P4 OCM derived chlorophyll image in the northeast Arabian Sea along Indian west coast.

Optical parameters

Optical properties of water (upwelling radiance, L_u ; downwelling irradiance, E_d and followed by water leaving radiance, L_w) describes apparent optical property of the water and is the signal that contains information about water constituents. Therefore, most of the empirical approaches for retrieval of oceanic constituents from satellite data require this parameter. Thus L_w is a basic and important parameter for any ship campaign to complement remote sensing technique development. Earlier cruises used Satlantic underwater radiometer which measured surface incident spectral irradiance, $E_s(\lambda) = E_d(0^+, \lambda)$, downwelled spectral irradiance, $E_d(z, \lambda)$, and upwelled spectral radiance, $L_u(z, \lambda)$ in 7 spectral channels centered at 412, 443, 490, 510, 555, 670, and 780 nm. The filters were custom designed to match the 10nm bandwidths required by the most of contemporary ocean colour sensors (e.g. SeaWiFS, OCM, MODIS, MERIS) CAL/VAL protocols. In

Table 1 Station locations of the cruise SS-244 with respective coordinates and depth

Stn. No	Date	Latitude ($^{\circ}\text{N}$)	Longitude ($^{\circ}\text{E}$)	Stn. Depth (m)
1	16.04.06	$10^{\circ} 43' 05''$	$74^{\circ} 46' 13''$	347
2	17.04.06	$11^{\circ} 59' 03''$	$74^{\circ} 29' 03''$	148
3	20.04.06	$16^{\circ} 20' 85''$	$72^{\circ} 11' 00''$	295
4	21.04.06	$17^{\circ} 18' 65''$	$70^{\circ} 13' 04''$	3275
5	22.04.06	$19^{\circ} 01' 08''$	$68^{\circ} 43' 41''$	3223
6	23.04.06	$20^{\circ} 34' 75''$	$67^{\circ} 09' 16''$	2930
7	24.04.06	$21^{\circ} 26' 66''$	$65^{\circ} 55' 26''$	2626
8	25.04.06	$22^{\circ} 18' 56''$	$67^{\circ} 21' 00''$	1247
9	26.04.06	$21^{\circ} 41' 65''$	$69^{\circ} 14' 31''$	42

this cruise hyperspectral radiometer having 1.2 nm resolution was used to obtain spectral information of water constituents. This profiling instrument is built upon the very successful Micro Pro design. This profiler allows to collect the data with a high spatial resolution in regions around a field station on typical oceanic and coastal waters with the influence of underwater currents.

Operation and processing of the hyperspectral underwater radiometer and derived data

The Ed and Lu optical sensors were attached to the profiler with positive locking quick releasing pins. The sensor cables of the instrument were connected accordingly. The power telemetry cable was connected to the instrument which was then, connected to the deck unit. Single level processing enables to process data over a single level that is from level 1a to level 1b and multi-level processing enables the user to process raw data up to level 2a, level 3a or level 4 (Prosoft User Manual 7.7, 2004). All intermediate processing levels are automatically processed with accompanying files (*.hdf) being produced. In this study, we have only included Lu, Ed, attenuated quantities; KL_u , KE_d from the hyper-spectral measurements and has been interpreted. Data has been retrieved from 1,5,10,20,30,40,50 meter depths in different stations for the spectral ranges of Lu, Ed, KE_d and KL_u and the available surface pigments data have been interpreted at different stations.

Results and discussion

The upwelling radiance (Lu) and downwelling irradiance (Ed) profiles have been plotted for all the 9 stations in our study area, of northeast Arabian Sea. Significant radiometric measurement profile was seen in all the stations. The peaks were seen around 420, 443, 490, 530, 670 nanometer wavelengths (Figs. 2, 3) in Lu and Ed profiles. *Trichodesmium* bloom has been significantly observed in the 2 and 9 stations, which are coastal stations with total depth less than 200 meters. In our study, we have observed

4 coastal stations (1,2,3 and 9) having depth <200m and 5 offshore stations (4,5,6,7 and 8) having depth >200m. The 1 per cent light was recorded at a maximum depth of 84m in offshore station and at a minimum depth of 35m in coastal stations. Deep chlorophyll maxima (DCM) were highest at station 4 at depth 65m and lowest at station 9 at depth 28m. Maximum Lu ranged between 0.42 and 1.55 $\mu W/cm^2/nm/sr$ and showed peaks at 380, 420, 450, 485 and 520 nm channels. Maximum Ed ranged between 45–160 $\mu W/cm^2/nm$ and showed peak at 380, 420, 485, 530 and 670 nm channels in the different stations. A descending trend was seen in Lu and Ed profiles from surface to deeper column waters. The attenuated downwelling irradiance (K-Ed) showed major peak in surface and column waters in the near infrared region around wavelengths 700 and 800 nm (Fig. 4). Even peaks observed in the channels other than in the visible range like in the ultraviolet region around 360 nm and in the near infrared region around 800 nm in the attenuated upwelling radiance (K-Lu) plot of offshore stations, might be due to bacterio-plankton, which needs to be understood with detailed analysis (Fig. 5).

The photograph of cyanophyte *Trichodesmium* bloom observed off Goa (around latitude 15° 23'N and longitude 73° 30'E) with yellowish brown colored water is shown in Fig. 6. We estimated 8 pigment types for all the 9 stations using HPLC measurements. Pigments dominance has been interpreted for all the stations and plotted as a bar diagram (Fig. 7). Maximum concentration was dominated by chlorophyll-a followed by Peridinin, Zeaxanthin, β -carotene, Pheophytin, Fucoxanthin and Chlorophyll-bc. The bloom station dominated by *Trichodesmium* indicated the presence of dominant pigments like Chlorophyll-a, Zeaxanthin, β -carotene and Pheophytin, (seen for stations 2 and 9). As seen from several studies, Zeaxanthin, β -carotene and Pheophytin are the other major pigments in *Trichodesmium* filaments in addition to Phycocyanin and Phycoerythrin. Their spectral response/reflectance was observed around 490, 530 nm (Subramaniam *et al.*, 2002). Moreth and Yentsch (1970) developed a method for extraction of phycoerythrin from

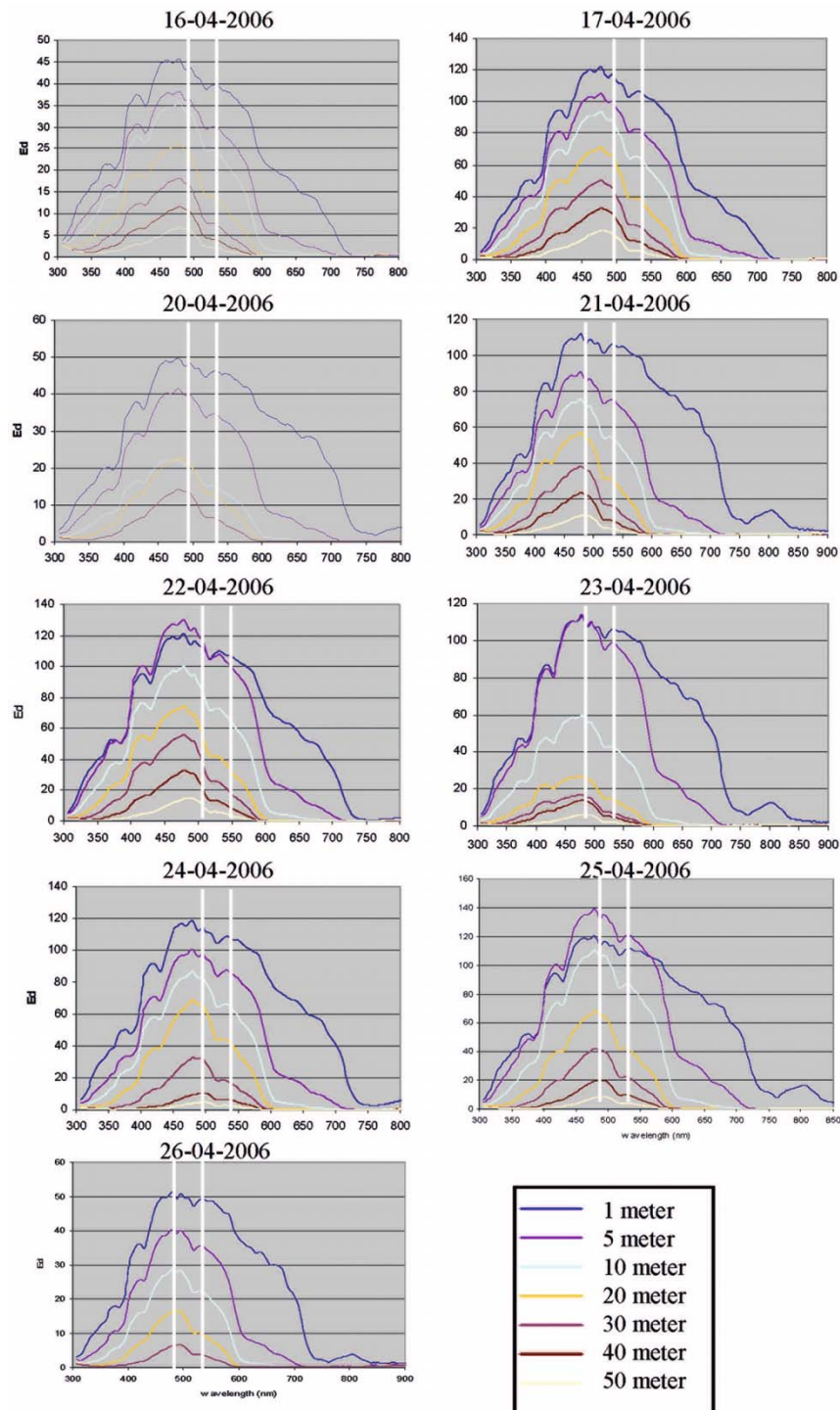


Fig. 2 Underwater hyperspectral radiometer derived downwelling irradiance (E_d) for different depths in the northern Arabian Sea for 9 stations.

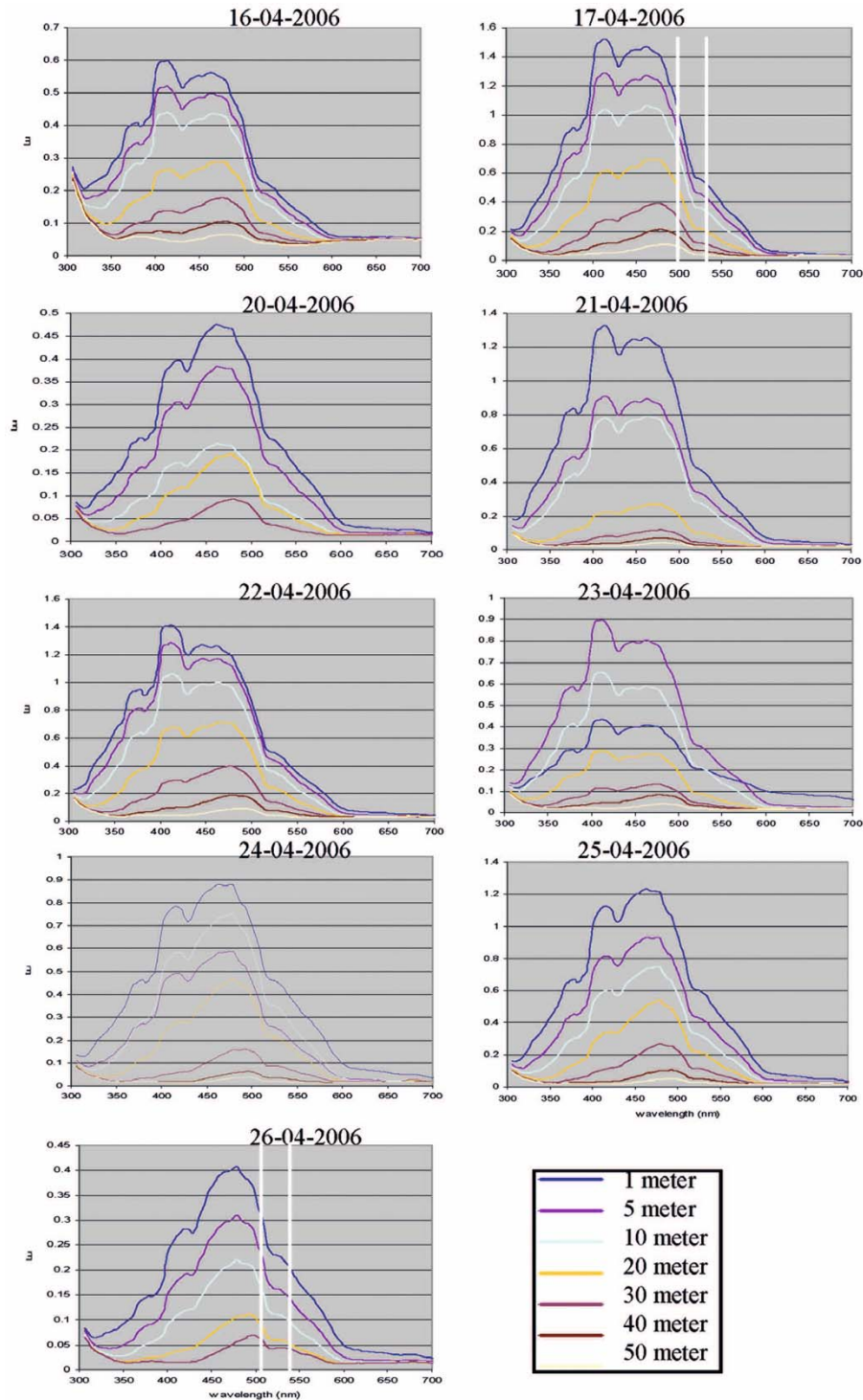


Fig. 3 Underwater hyperspectral radiometer derived upwelling radiance (L_u) for different depths in the northern Arabian Sea for 9 stations.

Trichodesmium spp. and showed that it had a single fluorescence emission peak around 565 nm when excited at 490 nm. Fujita and Shimura (1974) reported peaks in the visible portion of the spectrum at 500, 547 and 567 nm. Shimura and Fujita (1975) showed that these pigments were active in trapping light energy for photosynthesis. Others suggested that the amplitude of the absorption peak at 550 nm relative to that at 495 nm was higher in cultures of *Trichodesmium* isolated from the Sea of Japan (Ohki *et al.*, 1986).

The *in situ* measured chlorophyll concentration varied in the range 0.02–0.85 mg/m³. Most of the stations showed presence of *Trichodesmium* during this period. As the *Trichodesmium* species may be in different stages of growth, maturation and reproduction, only few stations showed algal blooming and discoloration of water in coastal regions. In our study, the bloom and dominant phytoplankton, *Trichodesmium* in stations 2 and 9 showed dips around the band 515 nm with its shifting nearby, which is due to the zeaxanthin, β -carotene and pheophytin pigments. The spectral absorption peaks for these pigments was in the range of 490–540nm as reported by several researchers and as displayed in Table 2 (Giorgi *et al.*, 1996; O’Dea *et al.*, 2002; Grabowski *et al.*, 2001; Barlow *et al.*, 2002). The absorption spectra of the methanol extracts revealed an additional peak at 475 nm due to caretenoids (Hogetsu and Watanabe, 1975). Populations where cyanobacteria were

prevalent were characterized by high photo-protective caretenoid absorption, particularly at 490 nm, most of the euphotic zone (Barlow *et al.*, 2002). The chlorophyll concentration was high among all all pigments in 9 stations. Therefore, the primary peak been seen at 443 nm in most of the stations. Even at around 490 nm, the peak has been seen in Lu and Ed and K-Lu profiles (Figs. 2–4); this normally

Table 2 Phytoplankton pigments and their absorption peaks

Serial No.	Pigments	Absorption peaks (wavelength, nm)
1	Chlorophyll-a	443 and 670; 685 (fluorescence)
2	Chlorophyll-b	450
3	Chlorophyll-c	590
4	Fucoxanthin	520
5	Peridinin	420
6	Zeaxanthin	500
7	β-carotene	490, 515
8	Pheophytin	536; 680 (excitation spectra)

*Pigments seen in bold letter has been found dominant in bloom stations (2,9)

[Source: <http://omlc.orgi.edu/spectra/PhotochemCAD/html/> and Barlow *et al.*, 2002]

Table 3 HPLC pigments (mgm⁻³) at surface of cruise FORV-244 (April 2006)

St. No.	Chl a	Chl b	Chl c	Fucoxanthin	Peridinin	Zeaxanthin	β -carotene	Pheophytin
1	0.151	0.002	0.005	0.066	0.055	0.045	0.011	0.041
2.	0.162	-	0.004	0.023	0.018	0.058	0.033	0.069
3.	0.234	0.003	0.002	0.078	0.035	0.041	0.038	0.041
4.	0.143	-	-	0.041	0.038	0.053	0.021	0.017
5.	0.023	0.004	-	0.023	0.064	0.031	0.024	0.039
6.	0.143	0.003	-	0.048	0.045	0.025	0.023	0.017
7.	0.162	-	-	0.032	0.075	-	0.011	0.032
8.	0.162	0.004	0.002	0.021	0.048	-	0.015	0.023
9.	0.321	-	-	0.038	0.037	0.152	0.095	0.095

*Bloom stations (2,9) shows higher concentration of zeaxanthin, β -carotene and pheophytin other than chlorophyll-a maxima in all stations

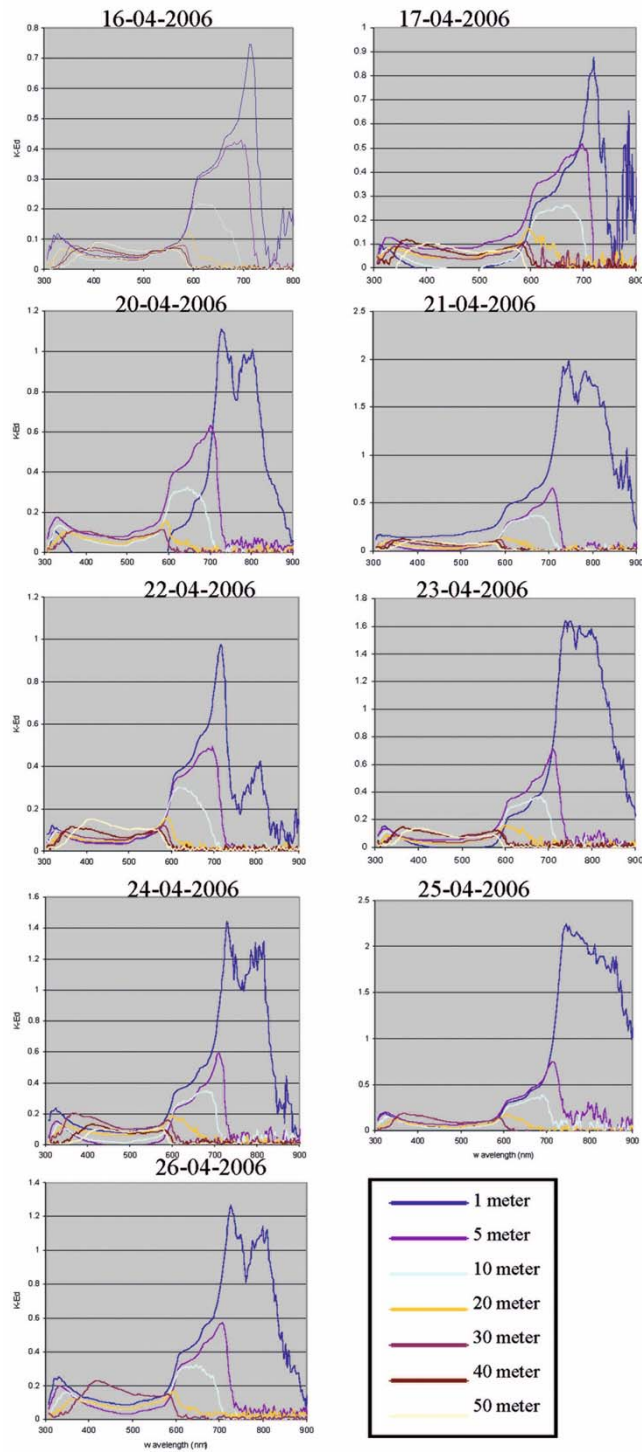


Fig. 4 Underwater hyperspectral radiometer derived attenuated downwelling irradiance (K-Ed) for different depths in the northern Arabian Sea for 9 stations.

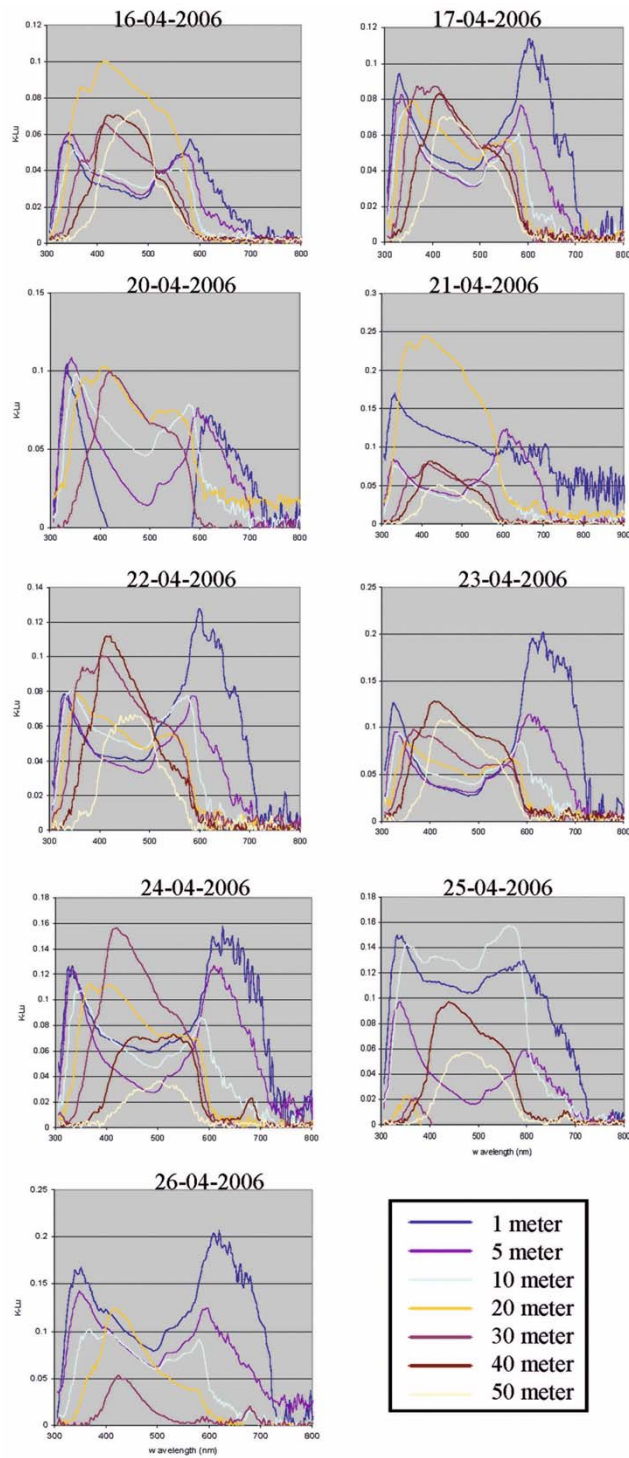


Fig. 5 Underwater hyperspectral radiometer derived attenuated upwelling radiance (K-Lu) for different depths in the northern Arabian Sea for 9 stations.

peaks due the *Trichodesmium* phycobillin pigments, like phycocyanin and phycoerythrin (Bjorkman and Adams, 1995; Subramaniam *et al.*, 2002). We do not have *in situ* pigment data for these two pigments, but the spectral profiles show peaks around 490 nm in bloom stations. The *Trichodesmium* bloom observed during the cruise and was identified using a electron microscope on board.

A dip in the Lu, Ed profiles was observed around the spectral range 500–540 nm wavelengths (Figs. 2, 3) for the pigments zeaxanthin, β -carotene and pheophytin (Fig. 7), which were major accumulating pigments during *Trichodesmium* bloom in the surface water and have their light absorption peaks at 490, 515 and 536 nm respectively (Figs. 1, 2). Overall, the carotenoids represent more than 100 different pigments, which absorb mainly between 450 to 550 nm while the phycobiliproteins main absorption is between 480 and 600 nm and there has been observation of shifting and variation in peaks of the individual pigments (Polívka *et al.*, 1999). Similar trend has been observed in the spectral plots of Lu and Ed profiles from our *in situ* measurement, the dip appeared

around 515 nm (Figs. 2, 3). HPLC analyzed pigments data at surface water indicates higher concentration of zeaxanthin, β -carotene and pheophytin in identified bloom stations (2,9) other than chlorophyll-a maxima in all stations (Table 3). Hence thorough and comprehensive *in situ* measurements and laboratory culture based spectral studies of species is required to confirm the individual pigments spectral peak, its shifting and responsible conditions. It appears that *Trichodesmium* species was dominant in most of the stations, but the surface density was high in few stations and hence the discoloration produced during their peak/blooming stage. Overall, *Trichodesmium*, the marine cyanophyte seems to be a dominant species during the season in the northeast Arabian Sea. From Figs. 1, 2, the chlorophyll absorption peak has been well observed, and varies in depths in descending order and peaks has been seen around 443 nm in most of the stations (Figs. 1, 2). In few stations, there was highly attenuated upwelling radiance (K-Lu) at around a wavelength of 590 nm in subsurface depths of 10, 20 and 30 meters, but not seen in the surface (Fig. 5). Detailed studies need to be done to



Fig. 6 Cyanophyte *Trichodesmium* bloom has been observed during the cruise on 19.04.06 off Goa.

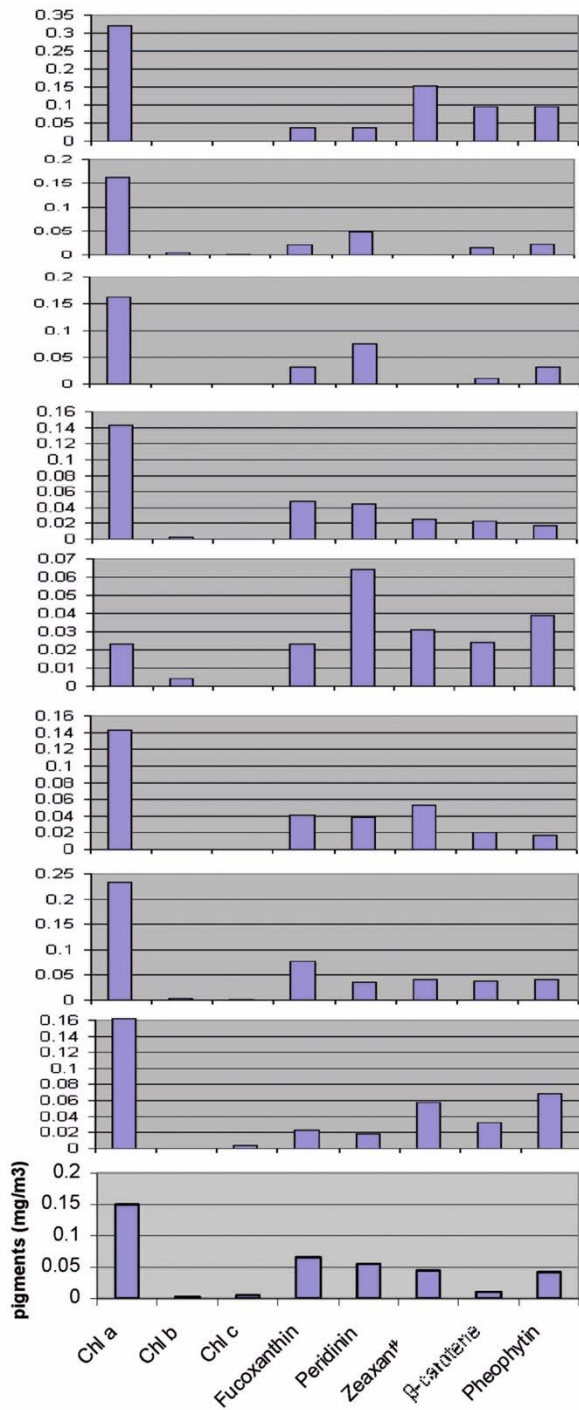


Fig. 7 HPLC derived surface water pigments for the 9 stations, displayed bottom to top (1-9) during the cruise period.

understand the vertical structure of phytoplankton in euphotic depth and to understand spectral property of various phytoplankton species.

From the profiles it can be seen that the entire north-east Arabian Sea, during the month of April, showed typical oligotrophic conditions in the oceanic waters. Chlorophyll profiles show narrower peaks and relatively low concentration of chlorophyll at the surface. DCM is usually located between 1–5% light levels approximately around 50–65m depth in most stations and was 28m in station 9, the coastal water-station.

Conclusion

Hyperspectral radiometer data analysis has enabled the identification of several wavelengths responsible for changing the in-water optical field during the bloom of *Trichodesmium* and other phytoplankton dominance. Significant radiometric measurement profiles have been observed in all the stations with peaks around wavelengths 420, 443, 490, 530, 670 nanometer in Lu and Ed profiles. The profiles of K-Ed shows major peak in the surface and column waters in the near infrared region around wavelengths 700 and 800 nm and even peaks were observed in the ultraviolet region around 360 nm in the K-Lu plot of offshore stations. The *Trichodesmium* bloom has been significantly observed in stations 2 and 9, which are coastal stations. During the bloom of *Trichodesmium*, the major accessory pigments showed a peak at wavelengths 523/526, 515 and 500 nm, which is responsible for the pigments of *Trichodesmium*; zeaxanthin, β -carotene, pheophytin, respectively, in addition to chlorophyll-a a dip in the Ed and Lu profiles have been seen around 515 nm in our study. Detailed *in situ* and culture based spectral analysis with respect to HPLC based pigments is required. This will help in developing satellite based bloom specific algorithm with precise measurements. Pigment specific algorithms also need to be focused on. It has been felt that space-time species diversity of the bloom should be studied along east-west track in the Northern Arabian Sea. The underwater response of phytoplankton and their optical characteristics

have been well retrieved and described in terms of hyperspectral measurements and HPLC data providing pigment composition. Even the coastal and open ocean optical properties can be well delineated using hyperspectral underwater radiometry.

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