

Detection of *Trichodesmium* bloom patches along the eastern Arabian Sea by IRS-P4/OCM ocean color sensor and by *in-situ* measurements

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The detection of blooms of the marine cyanobacterium *Trichodesmium* from space has been studied using high resolution ocean color imagery in the visible wavebands of the OCM monitor (Ocean Color Monitor) on the IRS-P4 satellite platform. The standard detection protocol developed by Subramaniam *et al.* [*Deep-Sea Res-II*, 49 (2002) 107-121], has been used in this paper. Localized bands of *Trichodesmium* were detected in OCM imageries of 16th, 18th, 20th and 22nd March 2002 in decreasing numbers with time. The patches were aligned approximately parallel to the shoreline, and distributed over the shallow waters off the west coast of India. An analogous search of *Trichodesmium* bloom patches for these days using available SeaWiFS (Sea Viewing Wide field of View Sensor) sensor revealed features of reduced spatial resolution compared to that observed by the higher resolution OCM sensor, and at locations further offshore. In a field study during 19th to 22nd March 2002, we encountered *Trichodesmium* patches (~ 90 km) off the coast of Goa. Microscopic analysis confirmed that these patches belonged to the *Trichodesmium erythraeum*. These field patches were further offshore from the positions occupied by the near-shore patches seen in the OCM imageries during 18th to 22nd March 2002. Radiometric measurements made in the cruise-detected patches show water leaving radiances averaging ~ 1 $\mu\text{W}/\text{cm}^2/\text{nm}$, below the detection threshold of the present satellite detection scheme. It is clear that further efforts are needed to improve the detection range of present protocols so as to detect the presence of less reflective *Trichodesmium* patches of the type encountered during our cruise.

[**Key words** : *Trichodesmium*, detection, Ocean Color Monitor, radiometer, trichomes, SeaWiFS, chlorophyll, Arabian Sea]

1. Introduction

Trichodesmium is a diazotrophic marine cyanobacterium that can fix nitrogen gas under fully aerobic conditions during daylight hours only, whilst evolving oxygen photosynthetically¹. The physical appearance of *Trichodesmium* at sea is that of red to orange colored swirls of sawdust on the sea surface arranged in extensive kilometer-long bands. Early literature referred to them as red tides or red water¹. At a microscopic level *Trichodesmium* exists in two known forms-namely as tuft colonies (*T. erythraeum*) which have the appearance of a clutch of bamboo shoots or as radial or puff colonies (*T. thiebautii*). The tuft form is common in Arabian Sea water^{2,3}. *Trichodesmium* blooms have been reported in various parts of the tropical Atlantic, Pacific and Indian oceans, in the Caribbean, and the South East China Sea^{1,4}. Along west coast of India, they have been sighted with regularity as extensive bloom patches in the near shore coastal waters off Goa, to the north

near the mouth of the Gulf of Khambat and around the Lakshadweep Islands in the months of February, March and April each year^{2,5}.

Despite its global presence in the tropical oceans and its significance as a major contributor to the global nitrogen cycle, it is difficult to detect *Trichodesmium* unambiguously from space. Current efforts to develop an empirical detection scheme have been based on laboratory optical measurements, and approximate optical models^{6,7}. Unfortunately these efforts have been frustrated by the lack of *in-situ* bio-optical measurements critically needed in validating bloom signatures by satellite⁸. Changes in wind conditions cause the rapid dispersal of bloom patches within a few hours (~3 hr). This results in variability of *Trichodesmium* patch sizes varying from a few meters wide to several kilometer long patches. Artifacts due to sediment plumes and cloud cover show up as highly reflective features in satellite images, which are very often indistinguishable from *Trichodesmium* patches, and have led to problems in their detection by satellite⁷.

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Recently, Subramaniam *et al.*⁷ have developed a multi-spectral classification scheme for detecting *Trichodesmium* in SeaWiFS imagery. The scheme is based on a standard remote sensing model of Gordon & Morel⁹ parameterized by inherent properties appropriate for the South Atlantic Bight, and the variation of spectral radiances extracted from a SeaWiFS feature believed to be due to *Trichodesmium*. The classification scheme was applied to SeaWiFS imageries of a spatially coherent *Trichodesmium* patch of the South Atlantic Bight which persisted from 27th October to 13th November 1998⁷. *Trichodesmium* specific chlorophyll concentrations of this patch varied from 0.5 to 3.0 mg/m³. Further, it was found that the bloom patch emitted normalized water leaving radiance nLw (at 490nm) values in excess of 1.3 $\mu\text{W}/\text{cm}^2/\text{nm}$, and this was then adopted as the main criterion for the classification scheme used in flagging pixels associated with *Trichodesmium*.

In the present study, we applied the Subramaniam *et al.*⁷ protocol to OCM imagery along the Eastern Arabian Sea coast in 2002. The imagery utilized was for the month of March, a period when *Trichodesmium* is known to proliferate in the region. Because of the availability of SeaWiFS imagery for the same period we were also able to compare the *Trichodesmium* detection capabilities of the OCM and SeaWiFS sensors. *Trichodesmium* have distinct optical properties because of their pigment constituents. The pigment content, absorption and back-scattering of *Trichodesmium* have been studied⁷ and certain spectral characteristics facilitate remote sensing of these organisms by satellite-mounted colour sensors. The aim of the present study is, to detect *Trichodesmium* in OCM (IRS-P4) images and to track the spatial extent of it. Patchiness of *Trichodesmium* blooms lead to a high variability in bio-optical measurements and this requires that novel ways of making measurements are necessary for a complete understanding of *Trichodesmium* phenomena.

The approach we utilized in this paper, is as follows –

a) First we study four time series flagged (not chlorophyll) images obtained from the Ocean Color Monitor (OCM) of the west coast of India for the period 16, 18, 20 and 22nd March 2002. The images depict the constant movement and variability in patch size and location. In order to independently confirm the presence of the features detected by OCM, we searched for them using SeaWiFs imageries for the

same period 16 to 20 March 2002. The detection capability of both satellite sensors is discussed.

b) We examine in detail the changes in the spatial spectral distribution of nLw (normalized water leaving radiance) across a selected OCM chlorophyll converted feature by tracking the radiance in different spectral bands in a horizontal transect from the open ocean towards, and then right across the selected patch which lies close to the coast. In doing so, the multi-spectral scheme which was adopted in this study is also presented in detail.

c) Direct validation through sampling of individual patches detected by OCM was not possible. As an alternative to this, we present *in-situ* data that was collected approximately 90 km away from the OCM detected features in a short cruise from 19th to 22 March 2002 (Fig. 1A). The study area is in the coastal waters off Goa on the west coast of India where South West monsoons and upwelling processes are most prominent during monsoon season.

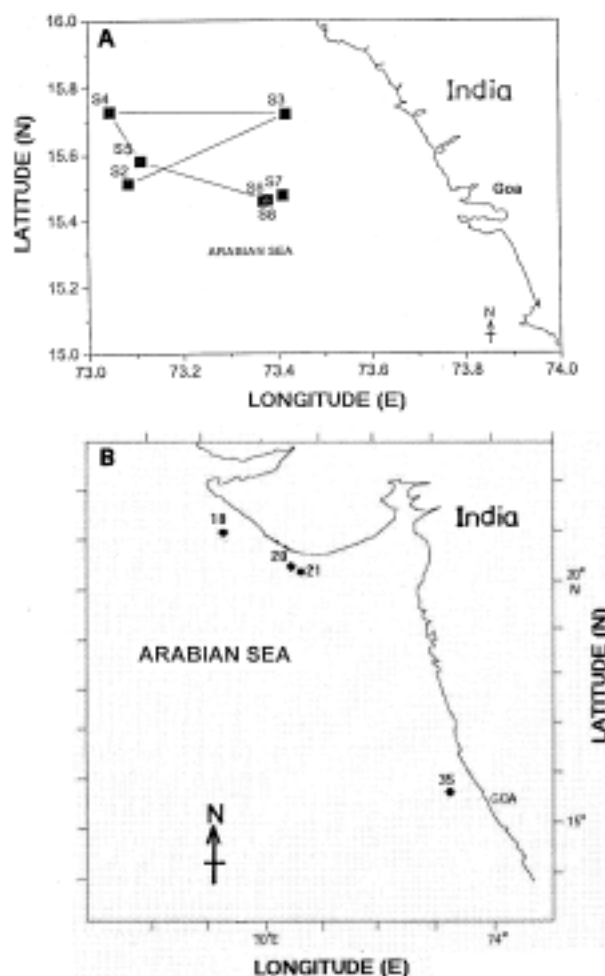


Fig. 1 — Station coordinates occupied on: A) *Sagar Sukti* cruise (SASU-16) and B) *Sagar kanya* cruise (SK-152)

d) *In-situ* experiments (Fig 1A) included a detailed phytoplankton taxonomic study of water samples, cell counting, chlorophyll concentration, water leaving radiance spectra, profiles of backscatter and diffuse attenuation coefficients in the water column, and spectral remote sensing reflectance.

2. Ocean Color Monitor (OCM) imagery from 16th to 22nd March 2002

2.1 Processing of OCM data

The raw LAC image data of OCM scenes for the west coast of India were obtained from the National Remote Sensing Agency [NRSA], Hyderabad, for the period 14th to 22nd March 2002. The processing sequence involves the conversion of level 0 OCM data to a HDF level 1 file and then a conversion to level 2 format. The technique for level 2 generation was to emulate the MOS (Modular Opto-electronic Scanner) sensor specifications in the input parameter setup to SeaDas (V4) (see ref13 NASA/CR -1998-206848) by modifying its msl12 code. OCM and MOS sensors both use push broom technology to scan a scene, and the emulation was made simpler due to this similarity in technology. The conversion of OCM data to level 2 was then straightforward as it exploited the advanced processing features offered in the SeaDas. The default SeaWiFS parameters for aerosol optical depth, transmittance, and extra terrestrial solar irradiance (Fo) values were used without change. In obtaining the final OCM imagery, the flag to detect *Trichodesmium* was selected. The flag setting feature is offered on the SeaDas software and is based on the multi spectral classification scheme of Subramaniam *et al.*⁷ for detecting *Trichodesmium* features from the

level 2 data. It may be noted that ‘flagged images’ carry coordinates of the features, which are used in plotting them.

A time series sequence of flagged OCM derived scenes for the 16th, 18th, 20th and 22nd March 2002 are shown in Fig. 2. Groups of patches (or streaks) shown in these figures are yellow in colour and circled, and from the point of view of the processing software represent detected *Trichodesmium*-like features that satisfied the multi-spectral classification scheme. The longest stretch of bloom patch was 74 km as seen on 16th March with width ranging from 6.6 km to 16 km. Subsequent days on 18th, 20th, and 22nd March showed typical patch lengths of 10 to 11 km in length, having maximum width in the range 5 to 2.2 km. Table 1 summarizes the maximum patch sizes for the 16,18,20 and 22 March 2002.

The 16th March (Fig. 2A) image shows the presence of at least 18 elongated long and short streaks. Subsequent images of 18th, 20th, 22nd show fewer patches, a marginal increase on 20th March (Fig. 2C) probably effected by variable wind conditions, and then a few patches (~ about 8) by 22nd March (Fig. 2D) as cloud cover (shown in white) spreads towards the coast and begins to obscure underlying features. There were no further features after 22nd March.

2.2 SeaWiFS imagery for the 16th March 2002

The processing of LAC SeaWiFS images applied the standard procedures in SeaDas, and are identical to that used in the processing of OCM data. As before, the *Trichodesmium* flag was set to look for features of this cyanobacterium using the same multi-spectral classification scheme. As a representative

Table 1 - Coordinates and dimensions of OCM detected patches

Date	16 March 2002	18 March 2002	20 March 2002	22 march 2002
Total area covered	3304 pixels 280.7 km ²	756 pixels 64.23 km ²	1359 pixels 115.46 km ²	258 pixels 21.92 km ²
Longest stretch	15.02N, 73.92 to 15.84N, 73.55E (73.92 km)	13.93N, 74.5E to 14 N, 74.4E (9.1 km)	16.07N, 73.41E to 16.17N, 73.42E (11.23 km)	
Maximum width observed in km	7.63, 6.6 km & 2.2 km. A thick patch at 1.43N, 72.93 E (16 km)	14.83N, 74 E to 14.92N, 73.99E (10.33 km)	4.0 km	2.2 km

▪ Length of coast ~ 500 km

▪ Extent of image from latitude 13 – 18N, longitude 69.8 – 76.N

OCM pixel is 236 m along track, 360 m across track e.g 1 pixel = 0.085 km².

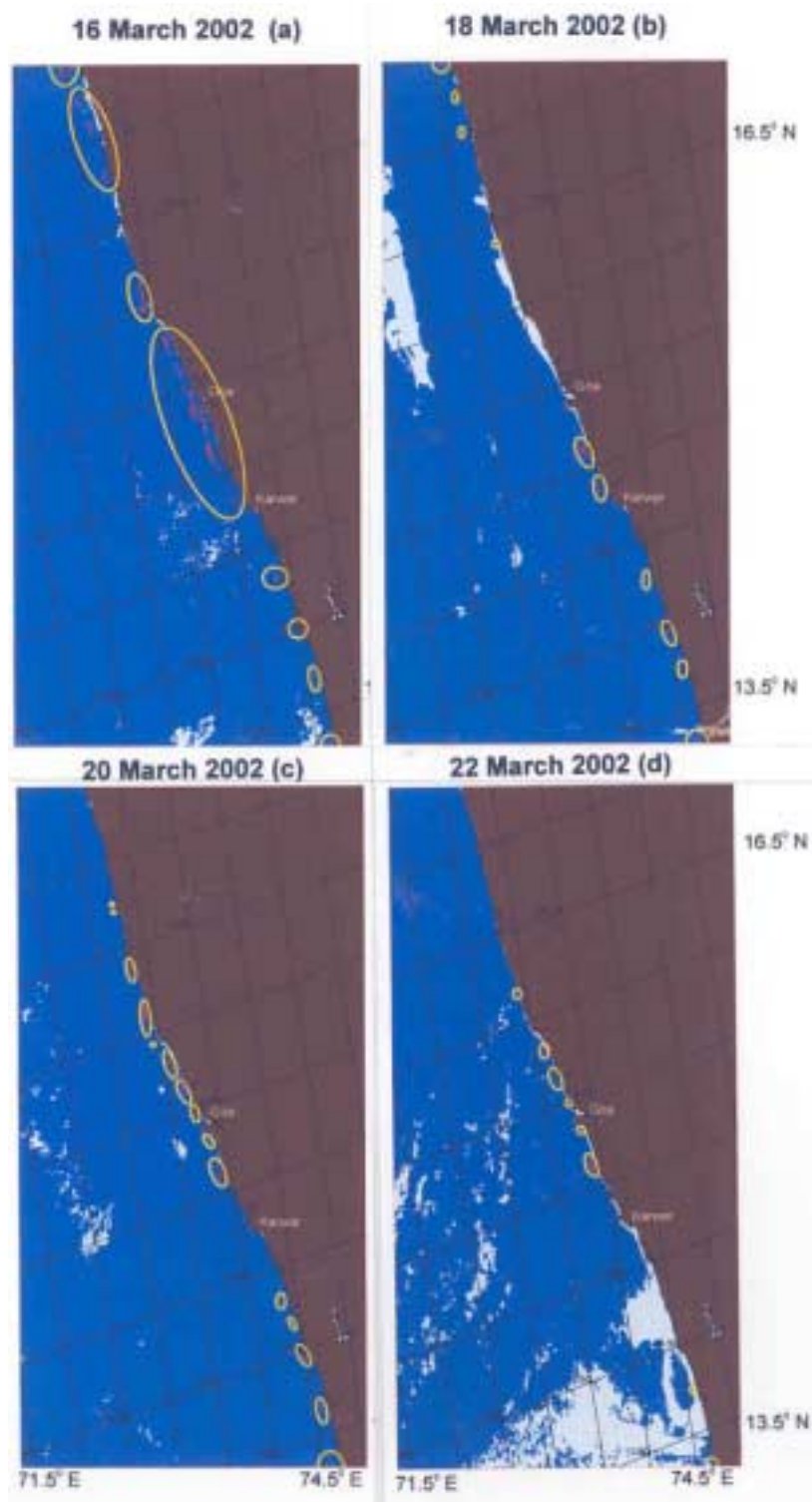


Fig. 2—OCM time series ‘flagged’ images of *Trichodesmium* bloom patches off the west coast of India near Goa, for (a) 16th March 2002 when bloom was intense (b) 18th March 2002 a decrease in the number of patches (c) 20th March 2002 a perceptible increase in patches and (d) 22nd March 2002 showing a few small diminishing patches with clouds approaching the coast

example for the period 16 to 22 March 2002, the flagged image of the SeaWiFS sensor for 16 March 2002 is shown in Fig. 3. We note the following:

- 1 The SeaWiFS detected features lack the detail in resolved spatial structure of the shapes seen in the OCM features. At best they contain 1 or 2 pixels of spatial resolution and no more.
- 2 Most of the SeaWiFS detected features are located further offshore and do not correspond to the near shore OCM features.

2.3 Qualitative reasons for the difference in patch detection capability between OCM and SeaWiFS

In assigning reasons to differences in detection capability we need to consider the trade-offs that can be obtained between pixel resolution, signal to noise ratio (SNR), and mean saturation radiance values of the two ocean color sensors. For example, SeaWiFS with its higher SNR features (2 to 3 greater than OCM) is better equipped to detect less reflective offshore bloom patches of *Trichodesmium* but would fail to register complete patch geometry with its lower pixel resolution. This seems to be the case in Fig. 3 of SeaWiFS. On the other hand, OCM with its higher saturation radiances in channels, lower SNR, and smaller pixel resolution did well in high backscatter radiances from shore patches (where sensitivity was not required), and in resolving the geometry of these features as in Fig. 4.

The patch sizes estimated by OCM show lengths of the order of ~ 10 km and typical widths of ~ 2 to 4 km (Table 1). The ground pixel resolution of the SeaWiFS sensor is $1\text{ km} \times 1\text{ km}$ and its higher sensitivity should have enabled the detection of these patches. When we compare the ground pixel resolution of OCM of $360\text{ m} \times 236\text{ m}$ to that SeaWiFS ground resolution of $1\text{ km} \times 1\text{ km}$, we infer that SeaWiFS is essentially averaging over a larger array size of $\sim 9 \times 9$ OCM pixels. The signal reaching the SeaWiFS sensor will then be expected to have mixed contributions from surface aggregations of *Trichodesmium* patches, clear water between patches, other phytoplankton, and colored dissolved organic matter due to the proximity of the patches to the coast, (see Table 2). This can result in a more flattened spectral shape with diminished *Trichodesmium* signal.

3. OCM water leaving radiances across a selected patch

In order to further characterize the nature of the satellite detected patches by OCM as being due to

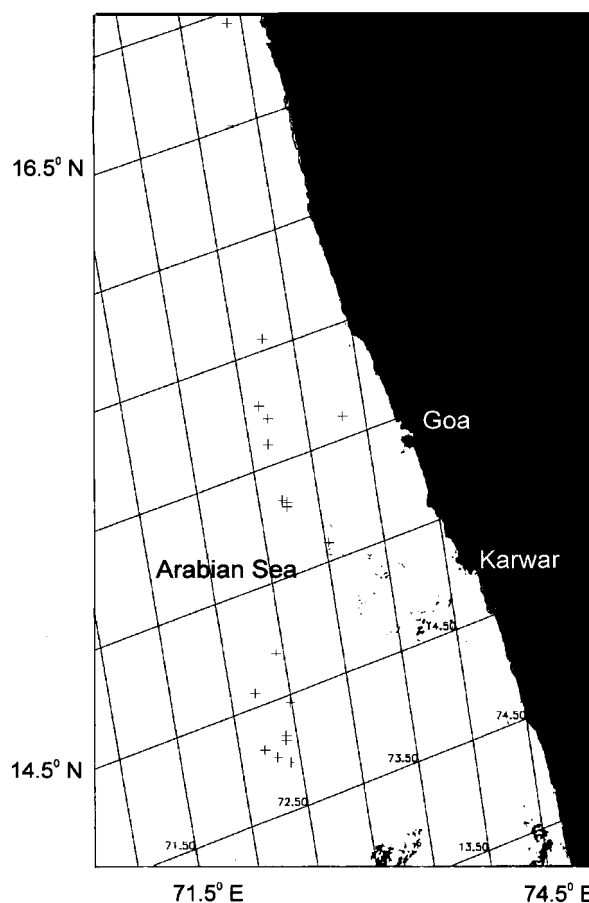


Fig. 3—SeaWiFS ‘flagged’ image of *Trichodesmium* for the 16 March 2002 along the west coast of India near Goa. The + (crosses) show the location where *Trichodesmium* was detected by SeaWiFS – most of which lie offshore.

Trichodesmium blooms, we consider the relative changes in spectral radiance distribution across a selected satellite detected feature. A processed chlorophyll based cloud-free OCM image for the 16th March 2002 of an area off the coast of Goa is shown in Fig. 4. The selected feature for analysis is shown at the bottom right hand corner of this figure. A south-west transect perpendicular to the coast has been marked as a red line to cut across the selected patch starting at a distance of ~ 90 km away from the coast and moving towards the patch near the coast.

The normalized water leaving radiance (nLw)* changes at the OCM center wavelengths at 414, 441, 485, 510, 556, and 670 nm are shown in Fig. 5. The changes in nLw ⁷ of Fig. 5 are summarized by the inequalities:

* The absolute values of OCM nLw radiance values in Fig. 5 should not be taken at face value, as it has uncertainties resulting from calibration affects, and the use of the standard SeaWiFS atmospheric correction that may not apply to coastal waters.

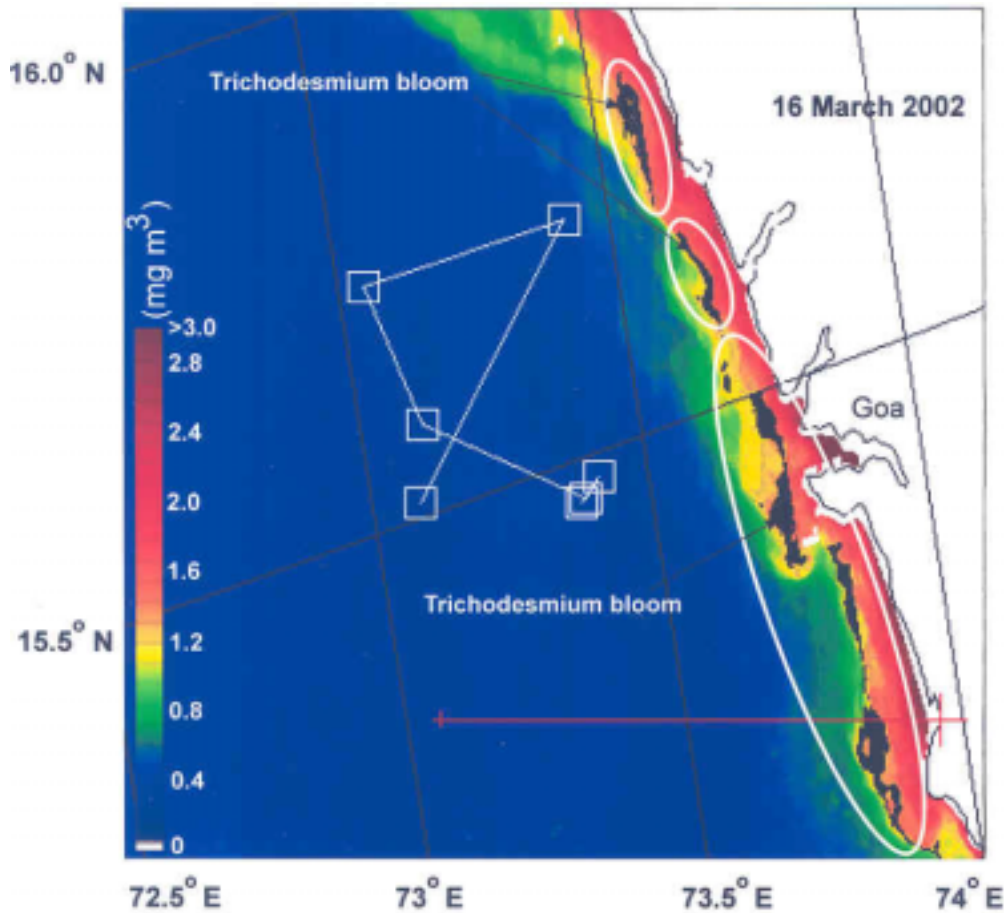


Fig. 4—A chlorophyll derived OCM image of the 16th March 2002 showing distinct elongation of *Trichodesmium* patches for an area off the coast of Goa. The cruise track of Sagar Sukti with square boxes representing stations is shown to be located away from the coast. The horizontal transect running from left to right at the bottom of the figure also across the *Trichodesmium* patch at the far bottom right corner of the figure.

Table 2 — Bio-optical observations on CRV *Sagar Sukti* (19th to 22nd March 2002) cruise

Date Stationnos.	Time(hrs)	Stn Depth(m)	Ratio of nLw(510)/nLw(443)	Chlorophyll a(mgm ⁻³)	Total Phytoplankton cell nos. × 10 ³ l ⁻¹ Trichomes(%)
19/3/2002 S2	15:00	72	0.660	0.55	57.8 (98.8 %)
20/3/2002 S3	8:19	40	---	2.0	62.64 (99.41%)
20/3/2002 S4	12:00	86	0.468	0.59	0.40 (18.41%)
20/3/2002 S5	14:03	86	0.567	---	----
21/3/2002 S6	11:20	70	0.675	126.75	690.9 (74.74%)
22/3/2002 S7	9:25	58	0.675	---	----
22/3/2002 S8	10:32	58	0.645	5.62 0.74	13.5 @ 0m (97.78%) 0.75 @ 5m (57 %)

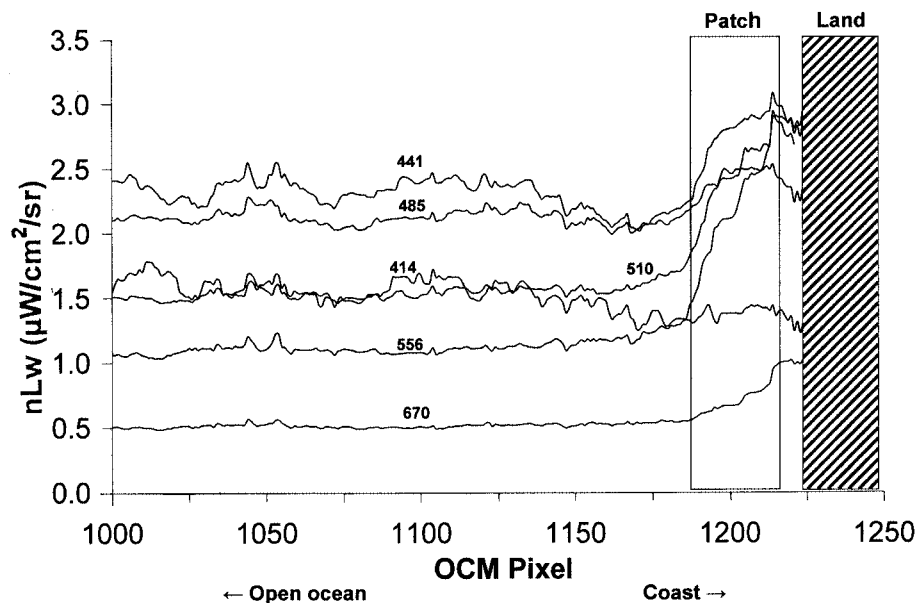


Fig. 5—Spectral variations of Normalized Water Leaving Radiance (nLw) evaluated along the transect (of Figure 4) for the 16th March image. Note that nLw (485 nm) attains the highest value within the patch, followed by radiances at 510, 441 and 555 nm.

- A Outside the patch : nLw (441) > nLw (485) > nLw (510) > nLw (556) > nLw (670)
- B Left edge of patch : nLw (485) > nLw (441) > nLw (510) > nLw (556) > nLw (670)
- C Inside the patch : nLw (485) > nLw (510) > nLw (441) > nLw (556) > nLw (670)
- D Right edge of patch : nLw (485) ~ nLw (510) ~ nLw (556) > nLw (441) > nLw (670)

In open waters, outside the patch, nLw(441) attains the highest value over all other wavelengths competing with nLw(485) i.e from pixel 1000 to pixel 1150. Inside the patch (which is our primary interest), there is a switch over with nLw(485), attaining the highest value ~ 2.5 to 3 $\mu\text{W}/\text{cm}^2/\text{nm}$ over all other wavelengths. Small changes are observed within the width of the patch and these are detailed below.

Subramaniam *et al.*⁷ have reported similar results in their analysis of SeaWiFS patch radiances for the South Atlantic Bight using empirical observation and model results. Three criteria were used by them in their multi-spectral classification scheme for flagging a pixel with a dominant *Trichodesmium* signal which are as follows :

- (I) $nLw(490) > 1.3 \mu\text{W}/\text{cm}^2/\text{nm}$ and $nLw(490) > nLw(412), nLw(443), nLw(555)$
- (II) $nLw(510) > nLw(443)$
- (III) $0.4 < [nLw(490) - nLw(443)] / [nLw(490) - nLw(555)] < 0.6$

(Note that the center wavelengths for the SeaWiFS sensor channels are slightly different from the OCM sensor)

Criteria I and II represent absolute and relative magnitudes of nLw radiance, and the III depends on the shape of the spectrum emitted by *Trichodesmium*. The inequalities that are listed in present analysis largely satisfy the Subramaniam *et al.*⁷ scheme albeit with some variability within the patch e.g :

- inside left of the OCM patch (see Fig. 5) the magnitudes of nLw at different wavelengths increase in the order 485, 441, 510, 556, 670 nm. This violates criterion II, but satisfies criterion I.
- in the centre of the patch of Fig.4, the nLw magnitudes for different wavelengths increase in the order 485, 510, 441, 556, 670 nm. This nLw variation satisfies criteria I and II.

The differences are small and may have a statistical variability linked to spatial distribution of *Trichodesmium* populations at sub-pixel scales.

4. Characteristics of *Trichodesmium* - *in-situ* data for the period 19th to 22nd March 2002

The objective of this section is to provide indirect evidence through *in-situ* measurements that the waters surrounding the OCM detected patches were replete with *Trichodesmium* cells even though these organisms were not detectable by satellite. The data presented here relate to a series of short term bio-optical measurements that were made during 19 to 22 March 2002 off the west coast of India on the coastal research vessel CRV *Sagar Sukti* of the National institute of Oceanography, Goa. The cruise track of the research

vessel is plotted on Fig. 4 also to show the relative closeness of the ship measurements to that of the *Trichodesmium* patches (marked in black) which were detected in OCM imagery of 16th March 2002.

4.1 Phytoplankton species identification in water samples

Different phytoplankton recorded are shown in Table 3. A diverse community of 14 species of diatoms, and 8 species of dinoflagellates were found present in surface waters with a dominant presence of *Trichodesmium erythraeum* at most stations. The radial puff species *Trichodesmium thiebautii* was also present at some stations as was *Navicula* spp.-a common member of the diatom family.

4.2 Variability in counts of trichomes and chlorophyll

The total phytoplankton cell counts are better expressed in terms of percentage counts of trichomes of *Trichodesmium* and “other phytoplankton” cells, and this is summarized in Table 2. A few observations are -

1. On the 20th March, station S3 was visited at 8:00 hrs and the percentage counts of trichomes of *Trichodesmium* spp. was high at 99.41%, with a total chlorophyll concentration at 2 mg/m³. Three hours later at station S4, these values had changed to 18 % trichome counts and 0.6 mg/m³. The patchiness of the bloom gives rise to significant variability in this type of measurement and as we shall see below in the radiometric data as well.

Table 3 — Phytoplankton species composition at stations occupied during of Sagar Sukti Cruise (19th to 22nd March 2002). Phytoplankton counts are expressed as (cell nos × 10³l⁻¹).

Station Number	S2	S3	S4	S6	S7	S8				
	0	0	0	0	0	0	5	10	20	
Depth (m)	0	0	0	0	0	0	5	10	20	
Genera / Species										
Diatoms :										
<i>Chaetoceros curvisetum</i>	0.075	-	-	-	-	-	-	-	-	
<i>Coscinodiscus</i> sp.	-	0.08	-	-	-	-	-	-	0.092	
<i>Melosira</i> sp.	-	-	0.082	-	-	-	-	-	0.092	
<i>Navicula</i> spp.	0.075	-	0.082	0.8	-	-	-	0.068	0.092	
<i>Nitzschia closterium</i>	0.225	0.16	-	0.8	-	-	-	0.068	-	
<i>Rhizosolenia</i> spp.	-	0.08	-	-	-	0.06	0.072	-	0.092	
<i>Rhizosolenia hebetata</i>	-	-	-	-	-	-	-	0.34	-	
<i>Streptotheca</i> sp.	-	-	0.082	-	0.163	-	-	-	-	
<i>Surirella</i> sp.	-	-	-	-	-	0.06	-	-	-	
<i>Thalassiosira subtilis</i>	-	-	-	172.6	-	-	-	-	-	
Dinoflagellates:										
<i>Ceratium</i> sp.	-	-	-	-	-	0.06	-	-	-	
<i>Scrippsiella</i> sp.	0.225	-	-	-	-	0.12	0.036	-	-	
<i>Gyrodinium</i> sp.	-	-	-	-	-	-	0.036	-	-	
<i>Oxytoxum</i> sp.	0.075	-	-	-	-	-	-	-	-	
<i>Peridinium</i> sp.	-	-	-	-	-	-	0.036	-	-	
<i>Protoperdinium</i> sp.	-	-	-	0.347	-	-	-	-	-	
<i>Prorocentrum micans</i>	-	-	0.082	-	-	-	-	-	-	
Other algae										
* <i>Trichodesmium erythraeum</i>	54.8	60.56	0.074	495.6	31.53	13.2	0.036	0.816	0.184	
* <i>Trichodesmium thiebautii</i>	2	1.76	-	20.8	-	-	0.396	-	0.276	
Unidentified	-	-	-	-	-	-	0.144	0.476	0.368	
Total Density	57.48	62.64	0.402	690.95	31.69	13.5	0.756	1.768	1.196	

- indicates species absent

* indicates trichome

2. A large patch of *T. erythraeum* was seen at station S6 on 21st March. The trichome counts at 10:12 hrs was 67.7%, and by 11:20 hrs had increased to 74.74% as the ship drifted towards the patch. At the patch, the total chlorophyll concentration was measured to be 127 mg/m³. It appears that phytoplankton other than *T. erythraeum* also contribute substantially to the total chlorophyll concentration. By the 22nd March, the total cell counts had dropped to $13.5 \times 10^3/l$ with, *Trichodesmium* contributing to 97.8 %, and rapidly diminishing in trichome counts to 57% at the 5 m depth. (see Table 2). This supports the decreasing number of patches seen in the OCM image of 22nd March.

4.3 Radiometric measurements in *Trichodesmium* dominated waters

We faced considerable difficulties in making radiometric measurements in waters having *Trichodesmium* bloom patches at the surface. The process of immersing a radiometer from a ship into a thick patch tends to disperse the patch revealing clear pools of water surrounding the radiometer. Qasim² made similar observations, which relate the concentration of 'clumps /m³' of *Trichodesmium* and the transparency of the water and also observed that when the 'clumps' are not very dense, the water column is uniformly distributed with cells up to depth of 10 m, and in this case the Secchi disc visibility can be as deep as 13 m. At higher concentrations of 'clumps,' the Secchi depth visibility is reduced to 9 m, and when the bloom was concentrated in the form of a thick surface scum layer, then scooping the scum by hand revealed that the water below was perfectly clear. Our present radiometric measurements, below strongly support these early observations of Qasim² and highlights the uncertainty of a definitive presence of a spectral signature of *Trichodesmium* signal in underwater radiometry.

5. Radiometric measurements

The standard set of irradiance (Ed) and radiance (Lu) spectra at the SeaWiFS bands were obtained from a free falling spectroradiometer¹⁰ (Satlantic Inc, Canada). We used a separate sky-viewing reference radiometer mounted on the fore-castle deck of the ship which continuously measured downward irradiance at the SeaWiFS wavebands at the time when in-water casts were being made so as to correct for variations in sky irradiance. Both wet and dry radiometers

connect to a deck control unit that synchronises the acquisition of the data streams, and then retransmits them to a computer. In order to avoid ship-shadow effects, the radiometer was cast from the aft of the ship. All radiometric quantities have been averaged over three or more successive casts of the spectroradiometer. The radiometric dataset of Ed and Lu enables one to derive the normalized water leaving radiances (nLw), and thus the remote sensed reflectance (Rrs), and the diffuse attenuation coefficient (Kd) at different wavelengths. We have used the standard least squares method¹¹ to estimate the attenuation coefficients K(Lu) and K(Ed) for propagating the values of Lu and Ed to the surface by log transforming the data of Lu and Ed respectively.

5.1 Underwater band-less spectra with $nLw(510) / nLw(443) < 1$ (R/V Sagar Sukti cruise)

The bio-optical measurements made at stations occupied during SASU-16 of the coastal vessel *Sagar Sukti* during 19-22 March 2002 (Fig. 1A) are summarised in Table 2.. A large patch of *Trichodesmium* bloom was seen on 21st March at 11:20 hrs, and also smaller patches on the 19th March. The normalized water leaving spectra at different stations are shown plotted in Fig. 6. All spectra exhibit shapes that show enhanced (or maximum) values of nLw at blue wavelengths (412 nm) akin to blue water spectra described by Desa *et al.*¹⁰. The ratio $nLw(510)/nLw(443) \sim 0.6$ is < 1 does not satisfy criterion 2 of the multi-spectral scheme which requires $nLw(510)/nLw(443) > 1$ (see section 3). Furthermore $nLw(490)$ is not the maximum radiance as would be required in criterion 1 of the scheme.

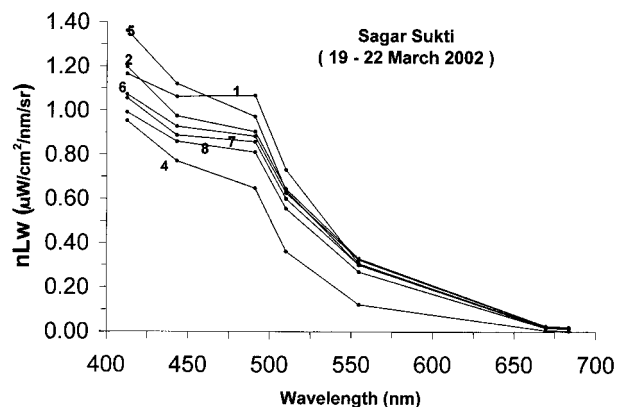


Fig. 6- Normalised Water Leaving Radiance (nLw) spectra at different stations on the Sagar Sukti Cruise (SASU-16) from 19th to 22nd March 2002 at the time when *Trichodesmium* features were detected by the OCM satellite sensor.

5.2 Backscatter and diffuse attenuation coefficients of 21st March 2000

Vertical profiles of the optical backscatter coefficients at 470 nm and 676 nm were measured with a Hydrosat 2 (Hobi Labs) and are shown in Fig. 7A for station S6 on the 21st March 2002. The profile of the diffuse attenuation coefficient K_d (490 nm) was derived from the irradiance measurements (E_d) of the radiometer, and is shown in Fig. 7B for the same station. These datasets were made when the ship was surrounded by a large patch of *Trichodesmium* in light blue waters, and moderate wind conditions. The backscatter profiles show that the water column below

and near the patch was optically homogeneous with very low backscatter coefficients namely b_b (470) $\sim 0.0030 \text{ m}^{-1}$ and b_b (676) $\sim 0.0015 \text{ m}^{-1}$ up to depths of 50 m. At depths > 50 m, backscatter coefficients increase as the instrument nears the sea bottom at 70 m indicating in all probability the presence of a benthic nepheloid layer (BNL)¹². The BNL is a zone of increased suspended particle concentration whose optical properties are directly influenced by physical and biological activity at the sediment-water interface. The constancy in the backscatter coefficients in the upper 50 m, and their low values support enhanced clarity of the water column with low suspended

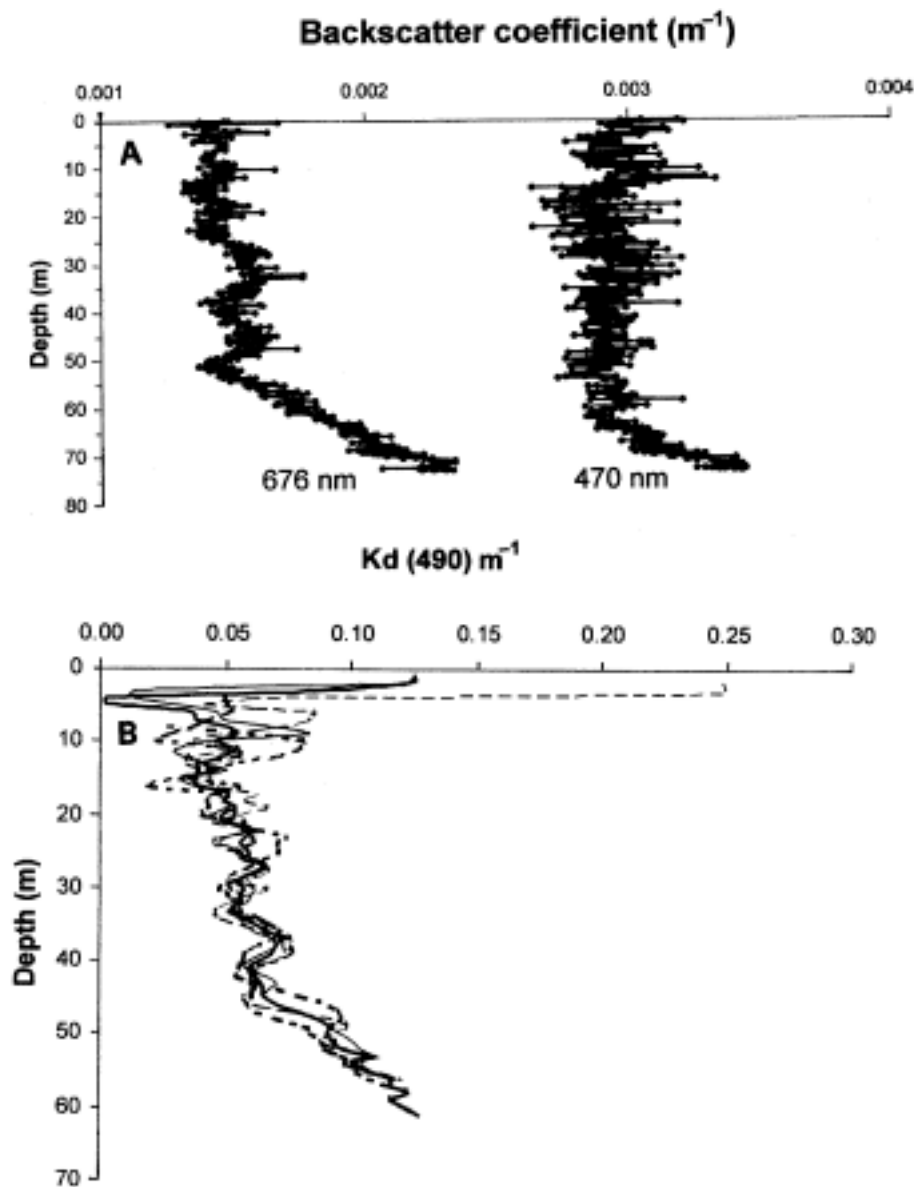


Fig. 7 — A)—Optical backscatter profiles at 470nm and 676 nm obtained on the 21 March 2002 at a *Saga Sukti* station where a large patch of *Trichodesmium* was visibly present. B) K_d —average diffuse attenuation coefficient profile at 490nm taken at same station as in Fig.6 on the 21 March 2002 The optical attenuation length is ~ 18 meters.

particle content. Further support for this is provided by K_d profiles measured at the same station and shown in Fig. 7B, which is the average of 4 successive optical casts at the station. Apart from surface disturbances in the top 10 m, either from wave or ship motion, we estimate a near constant value of $K_d = 0.055 \text{ m}^{-1}$ which converts to an optical attenuation length of $\sim 18.2 \text{ m}$. This ties up with the observation of Qasim² and present observations that the transparency of water is often enhanced in the presence of *Trichodesmium*. The profiles of backscatter coefficients at other stations in this cruise period were all closely similar to the 21st March station.

5.3 Underwater band shaped spectra with $nLw(510)/nLw(443) < 1$ on SK-152 cruise

A second example of the 'variability' in shape of radiometric spectra recorded in waters having a presence of *Trichodesmium* is shown in Fig. 8. The bio-optical measurements made at stations occupied on cruise SK 152 of *Sagar Kanya* during 30th March to 14th April 2000 (Fig. 1B) and are shown in Table 4. We observed thin surface accumulations of floating strands of *Trichodesmium* at 4 different stations whose coordinates are listed in Table 4 with measured total cell counts and percentage trichome counts at each station.

The shape of spectra in Fig. 8 show muted values of normalized water leaving radiance (nLw) at blue wavelengths (412 nm) with a developed band maximum at 490 nm and successively lower values at 510, 555, and 670 nm. The band structure is typical of coastal waters as classified by Desa *et al.*¹⁰. However, the ratio $nLw(510)/nLw(443)$ is larger ~ 0.8 , but still < 1 , and therefore contradicts criterion 2 of the multi-spectral scheme for satellite detection. The high trichome counts of $\sim 85\%$ at all these stations shows less variability than what we found during the CR/V *Sagar Sukti* cruises. Furthermore one would have expected that condition $nLw(510) \geq nLw(443)$ would be satisfied in these waters as predicted by the

optical model of Subramaniam *et al.*⁷ for high trichome counts.

5.4 Spectral band shapes specific to *Trichodesmium* and other phytoplankton

The optical model developed by Subramaniam *et al.*⁷ predicts nLw spectral band shapes for waters containing a combination of *Trichodesmium* and various other phytoplankton. In the case of *Trichodesmium*-specific spectra only, the effect of chlorophyll is to lift the radiance values at 510 nm and 555 nm above that of nLw at 443 nm, so that $nLw(510) > nLw(443)$. This happens beyond a threshold chlorophyll value of 0.5 mg/m^3 . This result was incorporated in the satellite detection scheme, and appears to work well. At higher chlorophyll concentrations of 10 mg/m^3 , the radiance nLw(555) achieves maximum values over all other wavelengths including the radiance at 490 nm. In the case of a combination of *Trichodesmium* and other phytoplankton species in varying percentages, the model shows close correspondence in spectral band shapes obtained on the SK 152 cruise radiometric data. The nLw spectra obtained on the Sagar Sukti cruise (Fig. 6) however, do not conform to the predictions of the

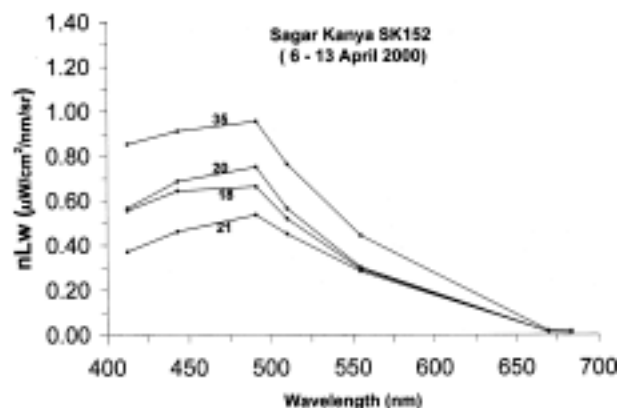


Fig. 8—Normalised Water Leaving Radiance (nLw) spectra at different stations on the Sagar Kanya Cruise SK-152 (1st to 13th April 2000) to the Arabian Sea. *Trichodesmium* was present at these stations.

Table 4 — Bio-optical observations on ORV Sagar Kanya SK -152 (30th March - 14th April 2000) cruise.

Station nos.	Date	Time (hrs)	Station depth (m)	Ratio $nLw(510) \div nLw(443)$	Surface chlorophyll (mgm^{-3})	Total Phytoplankton cell nos. $\times 10^3 \text{ l}^{-1}$ Trichomes (%)
18	6/04/2000	9:55	45	0.805	2.52	5.8 (81%)
20	7/04/2000	9:25	45	0.820	5.90	31.2 (83%)
21	7/04/2000	12:00	48	0.975	0.39	419.5 (85%)
35	13/04/2000	12.05	84	0.835	0.74	295 (88.5%)

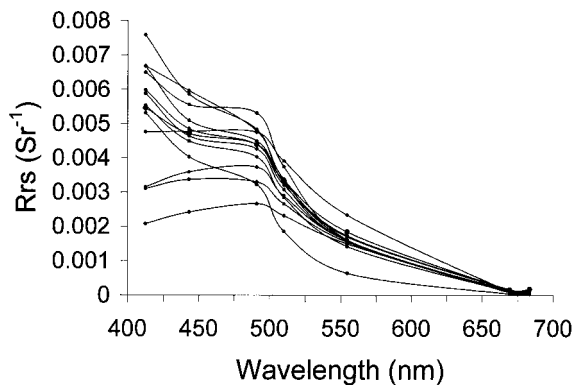


Fig. 9—Remotely Sensed Reflectance (Rrs) spectra derived from the nLw spectra data set of Figs 6 & 8 where *Trichodesmium* was present at the time when the radiometric measurements were made.

optical model, and are in a class of their own with enhanced values at blue wavelengths and typical spectral shapes of waters having low particle content.

5.5 Remotely sensed reflectance (Rrs) from cruise data

Remotely sensed reflectance (Rrs) spectra can be derived from the normalized water leaving radiance data of Figs. 6 and 8 discussed above. The nLw radiance values were converted to Rrs values just above the sea surface using the relation $Rrs(0^+) = [nLw/F_0]$ where F_0 is the wavelength dependent mean extra-terrestrial solar irradiance¹¹. The resultant Rrs spectra are shown in Fig. 9. At the blue end of the spectrum at 412 nm, Rrs varies over the range 0.002 to 0.008 while at 490 nm Rrs values are in the range 0.002 to 0.005. In the empirical model, first developed by Gordon & Morel⁹, the Rrs at any wavelength is directly related to the total backscatter coefficient (b_b) and the total absorption coefficient (a) at the same wavelength through the simple relation:

$$Rrs = 0.083 (b_b/a)$$

The coefficients (b_b) and (a) will contain contributions from pure water molecules, detrital matter, *Trichodesmium* cells, sediments and other phytoplankton accompanying the bloom. The physical reason for the muted values of the Rrs values in the range 0.002 to 0.008 are understandable if we approximate $Rrs \sim 0.083 (b_b / Kd)$ using measured values from the CRV *Sagar Sukti* cruise namely $b_b \sim 0.003 \text{ m}^{-1}$ and $Kd \sim 0.055 \text{ m}^{-1}$ to get $Rrs \sim 0.0045$. This is of the right magnitude and provides a physical reason that low backscatter and high transparency of these waters result in low Rrs values of Fig. 9.

6. Conclusion

The paper reports the first definitive images from space of *Trichodesmium* blooms in the Arabian Sea using the high resolution ocean color sensor OCM on board the Oceansat (IRS-P4) satellite. The contemporaneous SeaWiFS satellite images in the same period showed reduced detection capability of *Trichodesmium* near the coast, but was able to detect offshore traces of *Trichodesmium*. The discussion above on the comparison of OCM and SeaWiFS (section 2) indicates a requirement of a future satellite sensor with large dynamic range, low SNR, and high pixel resolution that could be used to study all surface algal blooms.

The *in-situ* biological and optical studies that were carried out in the vicinity of the OCM detected patches during 19th to 22nd March 2002 to characterize the OCM patches as being due to *Trichodesmium* have shown :

- Waters surrounding the OCM features were dominated by high trichome counts of *Trichodesmium* co-resident in the water column with a diverse community of diatoms and dinoflagellates. We surmise that the extent of its presence is more widely distributed than what is detected by satellite or by what meets the eye.
- The characteristic shape of the *in-situ* radiometric spectra did not carry a definitive signal due to *Trichodesmium* bloom as the data did not satisfy the criterion $nLw(510) \div nLw(443) > 1$ used in the multi-spectral satellite detection scheme and as a consequence they were probably not detected by the OCM colour sensor. The other reason is that the Remotely sensed reflectance values of this dataset were perhaps too low to register a strong enough signal at the satellite.
- Compounding the difficulties of making viable measurements of *Trichodesmium* patches at sea with *in-situ* radiometers, is the fact that these sensors, like satellite sensors, measure a composite optical signal having contributions from *Trichodesmium* cells, detrital matter, other phytoplankton species, and other particles - all of which tend to smear out the unique signal from *Trichodesmium* optics. Much higher concentrations of this cyanobacterium are needed to register and characterize the elusive *in-situ* *Trichodesmium* spectra. It is proposed that newer methods using hyper spectral radiometers mounted on Autonomous Underwater Vehicles [AUVs] riding below surface patches would capture more representative spectral data.

• Transparency of the water column has been a *common* effect that we have observed frequently in Arabian Sea field observations during the seasonal appearance and surface aggregation of *Trichodesmium* in the months of March and April. This needs to be understood more precisely from an eco-physiological and biochemical perspective.

The present detection scheme, as that of Subramaniam *et al.*⁷ for the remote detection of *Trichodesmium* works well in highly reflective dense bloom aggregations with satellite nLw values > $1.3 \mu\text{W}^{-1}\text{cm}^{-2}\text{nm}$ at 490 nm as that which was found in March 2002. The protocol is insensitive to bloom aggregates where nLw radiance is less than the threshold of $1.3\mu\text{W}^{-1}\text{cm}^{-2}\text{nm}$. Clearly, there is a need to account for all *Trichodesmium* aggregations in the ocean so as to arrive at good estimates of nitrogen fixation by this elusive cyanobacterium using hyper spectral radiometers, and new satellite payloads.

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References

- 1 Capone, D G, Zehr J P, Paerl H W, Bergman B & Carpenter E J, *Trichodesmium* a globally significant cyanobacterium, *Science*, 276, (1997) 1221 – 1229.
- 2 Qasim S Z, Some characteristics of a *Trichodesmium* bloom in the Laccadives *Deep-Sea Res.*, 17 (1970) 655-660.
- 3 Devassy V P, Bhattathiri P M A, & Qasim S Z, *Trichodesmium* phenomena, *Indian J. Mar. Sci.*, 7 (1978) 168-186.
- 4 Chang J, Chiang K P & Gong G C, Seasonal variation and cross-shelf distribution of the nitrogen-fixing cyanobacterium, *Trichodesmium*, in southern East China Sea, *Cont. Shelf Res.*, 20 (2000) 479-492.
- 5 Desa E S, Mascarenhas A, Matondkar S G & Suresh T, '*Bio-optical algorithms and validation experiments for IRS-P4 Oceansat Sensor*, Closure report, (National Institute of Oceanography, Goa, India) 2004.
- 6 Subramaniam A, Carpenter E J, Karentz D & Falkowski P G, (1999) Bio-optical properties of the marine diazotrophic cyanobacteria *Trichodesmium* ss.I Absorption and photosynthetic action spectra, *Limnol Oceanogr.*, 44(1999), 608-617.
- 7 Subramaniam A, Brown C W, Hood R R, Carpenter E J, & Capone D G, Detecting *Trichodesmium* blooms in SeaWiFS imagery, *Deep-Sea Res. II*, 49 (2002) 107 – 121.
- 8 O'Reilly J E, Maritorena S, Mitchell B G, Siegel D A, Carder K L, Garver S A, Kahru M & McClain C R, Ocean color chlorophyll algorithms for SeaWiFS, *J. Geophys. Res.*, 103 (1998) 24937- 24953.
- 9 Gordon H R & Morel A Y, *Remote assessment of ocean color for interpretation of satellite visible imagery*. A Review. (Springer) 1983.
- 10 Desa E S, Suresh T, Matondkar S G P, & Desa E, Seatruth validation of SeaWiFS Ocean Colour Sensor in the coastal waters of the eastern arabian sea. *Curr. Sci.*, 80, (2001), 854- 860.
- 11 Smith R C & Baker K S, The analysis of Ocean Optical Data. *SPIE* 489 (1984), 119-126.
- 12 Biscaye, P. E & S. L. Eittrheim Suspended particulate loads and transport in the nepheloid layer of the abyssal Atlantic Ocean, *Mar. Geol.*, 23, (1977) 155-172.