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Retrieval of Chlorophyll from the Sea-Leaving Radiance in the Arabian Sea

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ABSTRACT

Error estimates in chlorophyll retrieval in the sea from satellite data have always been higher compared to the errors in retrieval of sea surface temperature or wind speed from satellite data. This is due to the higher percentage of noise in optical signals compared to infrared or microwave signals reaching the satellite. The noise is introduced both at the sea surface itself and also while signal passes through atmosphere. In the present work, we have attempted to investigate the noise introduced at the sea surface. During the validation experiment of the optical sensor MOS-B onboard Indian Remote Sensing Satellite IRS-P3, simultaneous measurements of chlorophyll concentration and sea leaving radiance have been made along the satellite passes in the Arabian sea. The algorithms used in the present studies are not found to give satisfactory values of chlorophyll in about 30% of cases. The possible sources of errors in retrieving chlorophyll concentration have been discussed.

Introduction

Remote sensing of chlorophyll involves measurement of the spectral composition of radiation back-scattered from within the sea. This radiation contains signal for oceanic constituents, primarily for chlorophyll concentration. The photosynthesis occurring in the sea due to the presence of chlorophyll in phytoplankton selectively absorbs energies in certain wavelengths from the ambient light. As a result, the spectral composition of the sea-leaving radiation is altered as compared to the one that enters the sea. Numerous algorithms have been proposed to estimate chlorophyll

concentration from the sea-leaving radiance as received by a satellite carrying an ocean colour sensor (Gordon *et al.*, 1980, Hoge and Swift, 1986, Morel and Berthon, 1989, Parslow, 1991, Sathyendranath *et al.*, 1994). Development of a global algorithm to compute chlorophyll in the sea from the radiance received by a satellite has been delayed for several reasons. Firstly, much of the algorithm development is concerned with correcting the sea-leaving radiance for atmospheric effects that alter its spectral composition. The diversity of earth's atmospheres over the world ocean makes it nearly impossible to standardize the atmospheric correction procedure that can be globally applied. Moreover, the sea-leaving radiance is also affected by a host of other factors such as

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the sea state, ambient light field, cloudiness of the sky, turbidity of the seawater and yellow organic dissolved matter besides the chlorophyll. These extraneous factors add a significant amount of noise to the chlorophyll signal contained in the sea-leaving radiance.

In this paper, we have attempted to study some of these extraneous factors that alter the chlorophyll signal in the sea-leaving radiance at the sea surface. The purpose of considering sea-leaving radiance *at the sea surface itself (rather than use satellite derived sea leaving radiance)* is to eliminate the atmospheric noise, which comes into play only after the sea-leaving radiance has penetrated into the atmosphere.

We have tested two common algorithms to study the relationship between chlorophyll-a content of the sea and the sea-leaving radiance, namely, the single ratio algorithm used earlier for CZCS data (Gordon and Clark, 1980) and the two factor algorithm developed for processing the SeaWiFS data (Tassan, 1994). This is in view of the fact that the new satellites carrying ocean colour sensors such as Oceansat 1 have channels similar to CZCS and SeaWiFS. We have made use of sea-truth data collected during the validation campaign (1996-1998) of the experimental ocean colour sensor MOS-B, flown onboard the Indian satellite IRS-P3.

Sea-truth Collection

An experimental ocean colour sensor MOS-ES (Modular Opto-electronic Scanner) developed by DLR, Germany, was flown on Indian satellite

IRS-P3, launched in March 1996. MOS-B has 13 channel sensors operating in visible and near infrared region of the electromagnetic spectrum with a spectral bandwidth of 10 nm and a swath of 200 km on the ground. Details of MOS-B sensor are given in Table 1 (Navalgund, 1997). A sea-truth collection campaign for MOS-B validation was carried out during the years 1996-1998 in the Arabian Sea. The area covered during the campaign was eastern Arabian Sea, along the west coast of Indian subcontinent (see Fig. 1 for locations of sea-truth collection). During the campaign, simultaneous measurements of oceanic and atmospheric parameters along the MOS-B passes have been carried out. In all, data from 42 synchronous locations were collected. Since the swath of MOS-B was only 200 km, only a few synchronous locations were identified during each campaign.

Chlorophyll - a concentration was measured fluorometrically at different depths upto the euphotic zone. Suspended sediments were measured by filtration method. Upwelling and downwelling light at various depths was measured for the spectral range from 400 to 800 nm using the LICOR radiometer. The upper air data on humidity and temperature were collected through radiosonde balloons along with standard surface meteorological parameters. Data on aerosol distribution and atmospheric optical depths were also collected during the campaign. This communication deals with only data on chlorophyll concentration in the euphotic zone and the sea leaving radiance.

Table 1: Specifications of the Modular Optoelectronic Scanner (MOS-B) optical colour sensor onboard Indian Remote Sensing Satellite IRS P3 (Navalgund. 1997)

Spectral range	408-1010 nm
No. of channels	13
Channels (nm)	408, 443, 485, 520, 550, 570, 615, 685, 750, 870, 815, 945, 1010 nm
Spectral bandwidth	10nm
Swath width	200 km
Pixel size	0.52 x 0.52 km

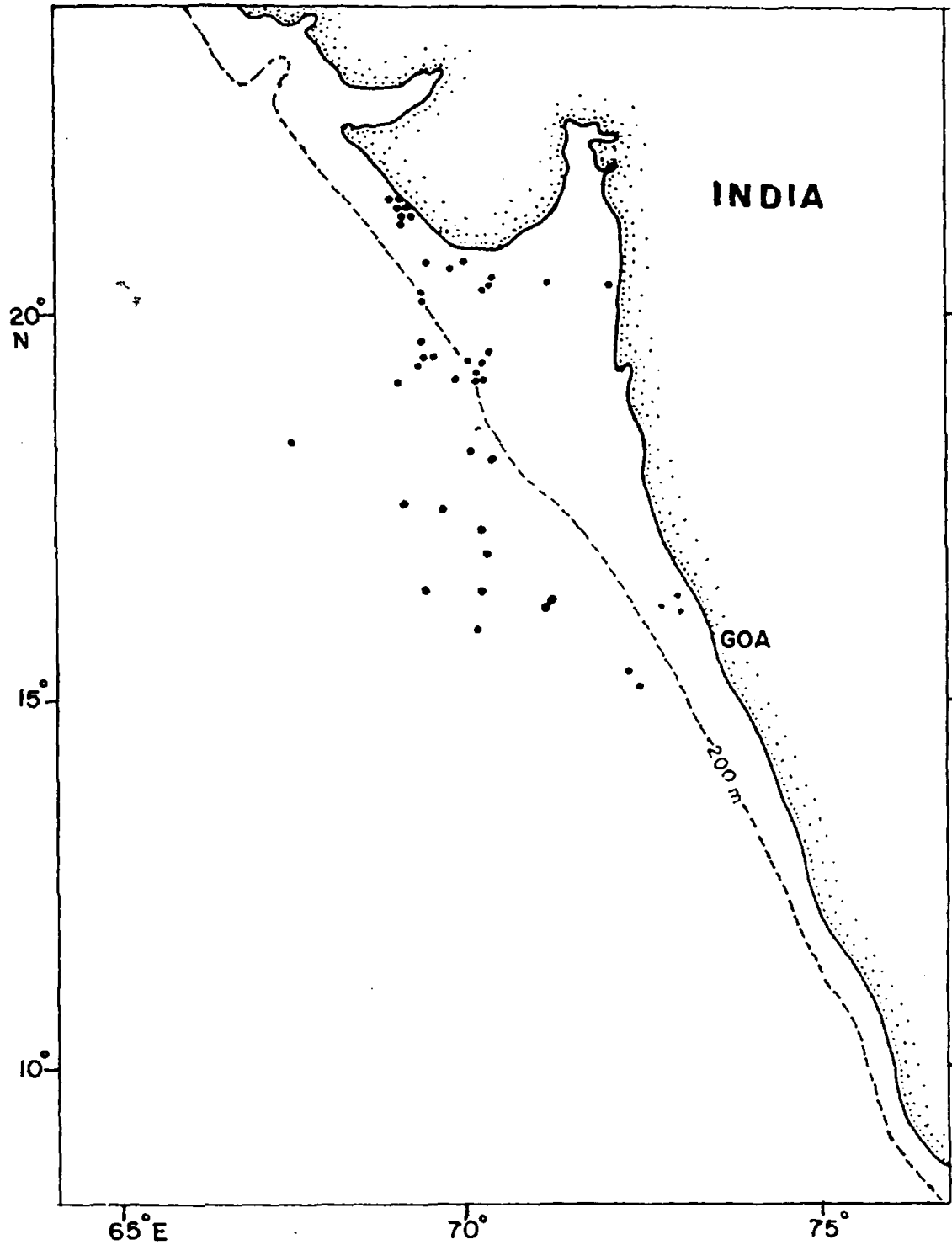


Fig. 1. The figure shows station locations in the Arabian Sea where bio-optical measurements were made during the sea-truth collection programme for the validation exercise of MOS-B onboard IRS-P3.

Algorithms for Chlorophyll Retrieval

The single ratio algorithm uses ratios of sea-leaving radiance in two different spectral bands, mainly the blue and green wavelengths to estimate chlorophyll (Gordon *et al.*, 1980). The general form of the expression is,

$$C = A * (L_{ij})^B \quad (1)$$

where C is the chlorophyll-a concentration in mg.m^{-3} , L_{ij} is the ratio of sea-leaving radiance at two spectral bands i and j and A and B are empirical constants. The expressions are

$$C_{13} = 1.15 \times [L(440)/L(560)]^{-1.42} \text{ for } C < 1.0 \text{ mg m}^{-3} \quad (2)$$

$$C_{23} = 3.64 \times [L(520)/L(560)]^{-2.62} \text{ for } C > 1.0 \text{ mg m}^{-3} \quad (3)$$

The two factor algorithm was proposed by Tassan (1994) for the retrieval of chlorophyll, suspended sediments and yellow substances using SeaWiFS data. For the present study, a modified form of algorithm used by Tassan (1994), which is proposed by Naval Gund (1997) to suit MOS-B wavelengths has been used. In the modified form, a new variable X is used for regression analysis between sea-leaving radiance and ship measured surface chlorophyll concentration as given below:

$$X = [L(443)/L(570)] * [L(408)/L(485)]^{-1.2} \quad (4)$$

$$\log(C) = -0.13 - 1.07 * \log X + 0.12 * \log X^2 \quad (5)$$

where notations have their usual meanings as given in equations (2) and (3). Wavelengths 443 and 570 nm are close to the chlorophyll absorption maximum and minimum whereas, wavelengths 408 and 485 nm are on the either side of the main chlorophyll absorption peak (compensating term).

Irradiance values used in both the above algorithms are at their respective central wavelengths. Satellite derived irradiance is usually integrated over 10 or 20 nm interval because if satellite were to measure exactly at the

central wavelength, the quantity of radiation received from the foot-print on the surface will be too low to be sensed by the sensors because of atmospheric attenuation. While at the sea surface, the radiance is recorded as soon as it emerges out of the sea and hence, this constraint does not apply.

It may be noted here that radiometers measure irradiance E, while algorithms use radiance values L. Since L is proportional to E ($L = E/Q$ for Lambertian surface and $L = E/Q$ (Q varying between 3 and 5) for non-Lambertian surface, see Morel and Gentili, 1991), their ratios at a given location become analogous.

Results and Discussion

Table 2 shows measured chlorophyll values at all locations along with those estimated from sea leaving radiance using the two algorithms. The symbol star (*) in the performance column of Table 2 indicates success of the algorithm. Figs. 2A and 3A are graphic representation of the above results for matching points while Figs. 2B and 3B show the graphic results for the entire dataset. Table 3 shows correlation coefficients and other statistical parameters that describe performance of both CZCS and SeaWiFS algorithms.

It appears from Table 2 that SeaWiFS algorithm with 31 matching points is marginally better than CZCS algorithm in which only 28 points match. However, Table 3 shows higher correlation coefficient for CZCS matches (0.400 for CZCS as against 0.156 for SeaWiFS) with a slightly smaller standard predictive error (0.201 for CZCS as against 0.216 for SeaWiFS). Thus the effect of compensating term used in the SeaWiFS algorithm to account for the presence of suspended sediments and yellow matter has resulted in only marginally increasing the number of matches but not in increasing their correlation coefficient.

It is seen from results in Table 2 and Figs. 2 and 3 that agreement between measured and

Table 2: Comparison between measured values of chlorophyll and values estimated from sea leaving radiance at corresponding locations.

Sr. No.	Date dd/mm/yy	Latitude °N	Longitude	Measured Mg/m**3	CZCS Algor	Performance	SeaWifs Algor	Performance
01	16/10/97	19:02	70:49	0.02	0.12		1.40	*
02	16/10/97	16:00	70:44	0.02	0.11		0.03	*
03	15/10/97	19:02	70:49	0.03	0.14		0.03	*
04	17/01/98	13:36	74:08	0.03	0.35		0.04	*
05	08/10/97	16:36	73:15	0.07	0.08	*	0.08	*
06	21/01/98	18:22	70:35	0.07	0.51		0.35	
07	09/01/98	19:03	70:47	0.10	0.88		0.09	*
08	11/10/97	21:12	69:50	0.11	0.67		1.30	
09	16/01/98	13:40	74:00	0.12	0.14	*	0.32	
10	20/01/98	20:38	70:52	0.14	0.13	*	0.15	*
11	14/10/97	21:32	69:35	0.14	1.50		0.66	
12	10/04/97	17:40	69:16	0.16	0.20	*	0.15	*
13	09/10/97	18:13	70:53	0.17	0.15	*	0.21	*
14	20/01/98	20:32	71:14	0.17	0.17	*	1.48	
15	15/04/96	19:30	70:28	0.19	0.16	*	0.15	*
16	12/10/97	19:27	69:36	0.19	0.18	*	0.19	*
17	18/04/96	12:43	72:25	0.20	0.18	*	0.25	*
18	12/10/97	19:29	69:56	0.20	0.17	*	0.22	*
19	10/10/97	19:41	69:51	0.20	0.18	*	0.23	*
20	05/03/96	18:55	66:23	0.21	0.22	*	0.26	*
21	15/04/96	19:12	70:34	0.21	0.25	*	0.21	*
22	15/10/97	19:15	70:46	0.21	0.22	*	0.22	*
23	17/01/98	13:05	73:57	0.21	0.24	*	0.62	
24	15/04/97	20:11	70:47	0.22	0.19	*	0.28	*
25	14/04/96	16:31	70:27	0.25	0.31	*	0.31	*
26	18/04/96	12:35	72:40	0.28	0.28	*	0.31	*
27	11/10/97	20:59	70:07	0.34	1.05		0.39	*
28	17/04/96	15:36	72:56	0.38	0.36	*	0.36	*
29	07/10/97	16:21	73:16	0.38	0.39	*	0.36	*
30	10/04/97	17:46	69:25	0.39	0.42	*	0.38	*
31	16/04/96	16:45	69:50	0.40	0.35	*	0.35	*
32	04/03/96	19:44	64:59	0.47	0.53	*	0.46	*
33	16/04/97	18:43	70:36	0.48	0.46	*	0.46	*
34	19/01/98	20:29	70:51	0.51	0.12		0.22	
35	17/04/97	16:23	71:22	0.54	0.48	*	0.45	*
36	21/01/98	19:07	70:36	0.54	0.22		0.48	*
37	13/04/97	21:31	69:36	0.54	2.81		0.22	
38	08/10/97	16:36	73:15	0.57	0.55	*	0.61	*
39	12/04/97	20:16	69:49	0.59	0.30		0.23	
40	02/03/96	20:49	70:18	0.60	0.92		0.55	*
41	11/04/97	20:18	69:51	0.71	0.79	*	0.26	
42	13/10/97	21:38	69:34	0.99	1.13	*	1.07	*

The symbol '*' in the performance column indicates that the estimated value was in agreement with the measured value in accordance with the criterion described in the text.

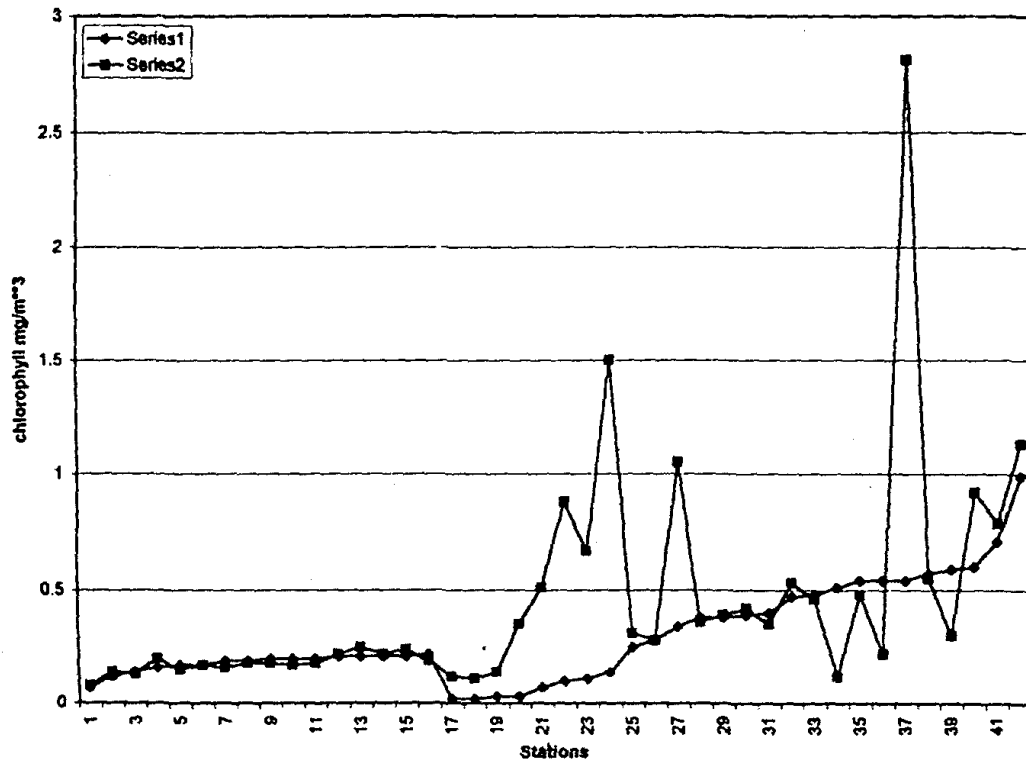
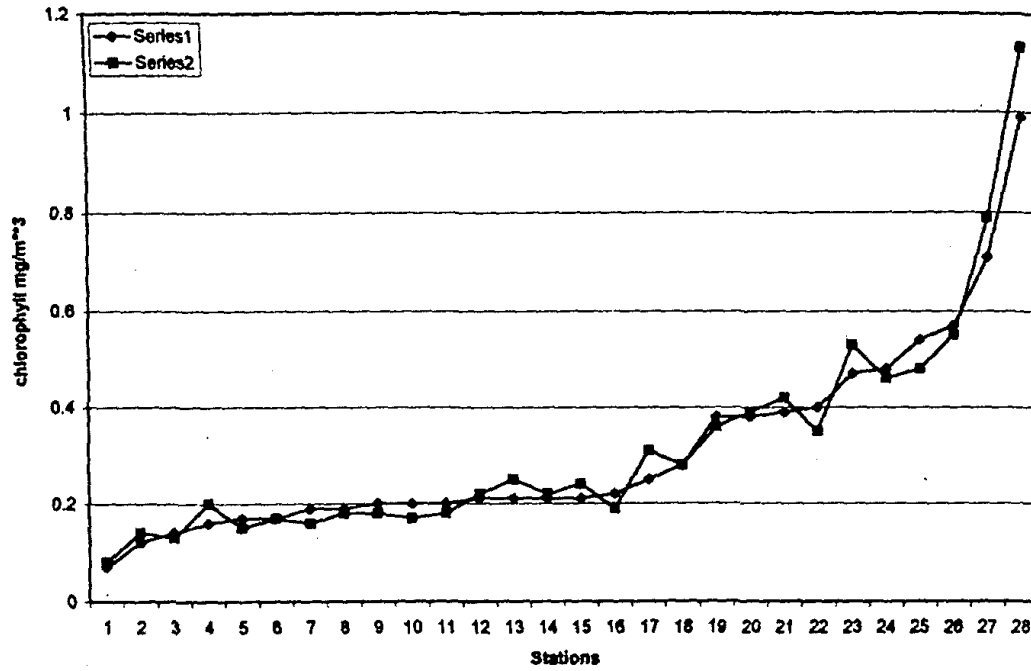


Fig. 2 (A and B). The figures are a graphic representation of performance of CZCS algorithm. Series 1 shows chlorophyll values measured in situ while series 2 shows chlorophyll values estimated from sea leaving radiance. Figure A shows results for matching data points while figure B shows results for the entire dataset.

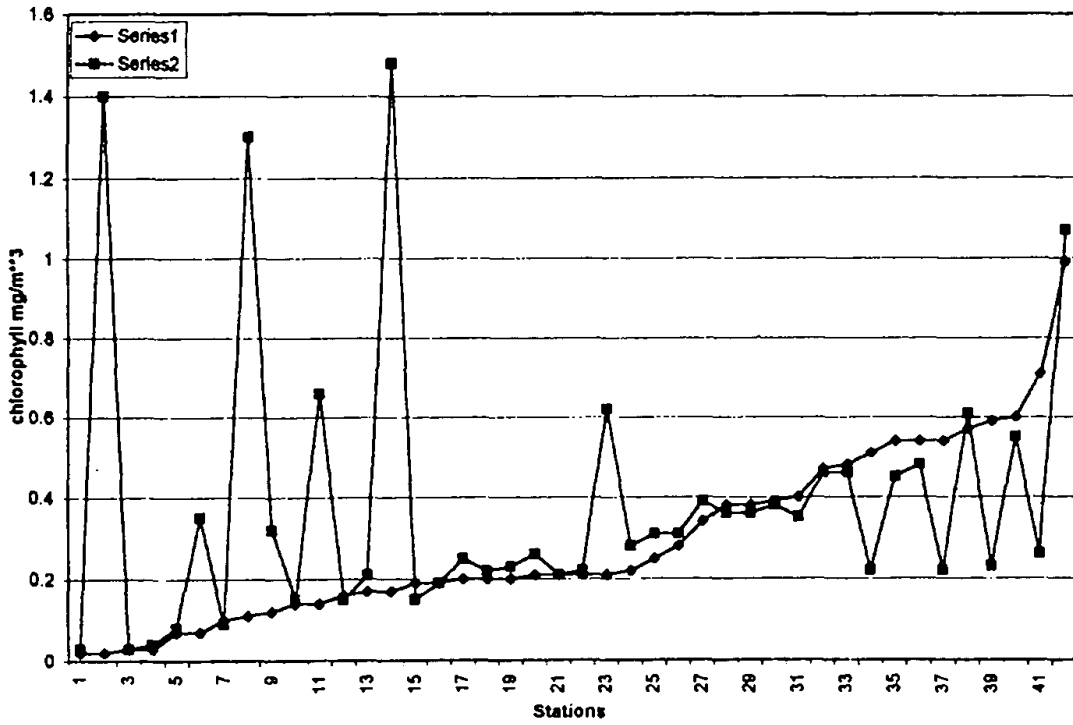
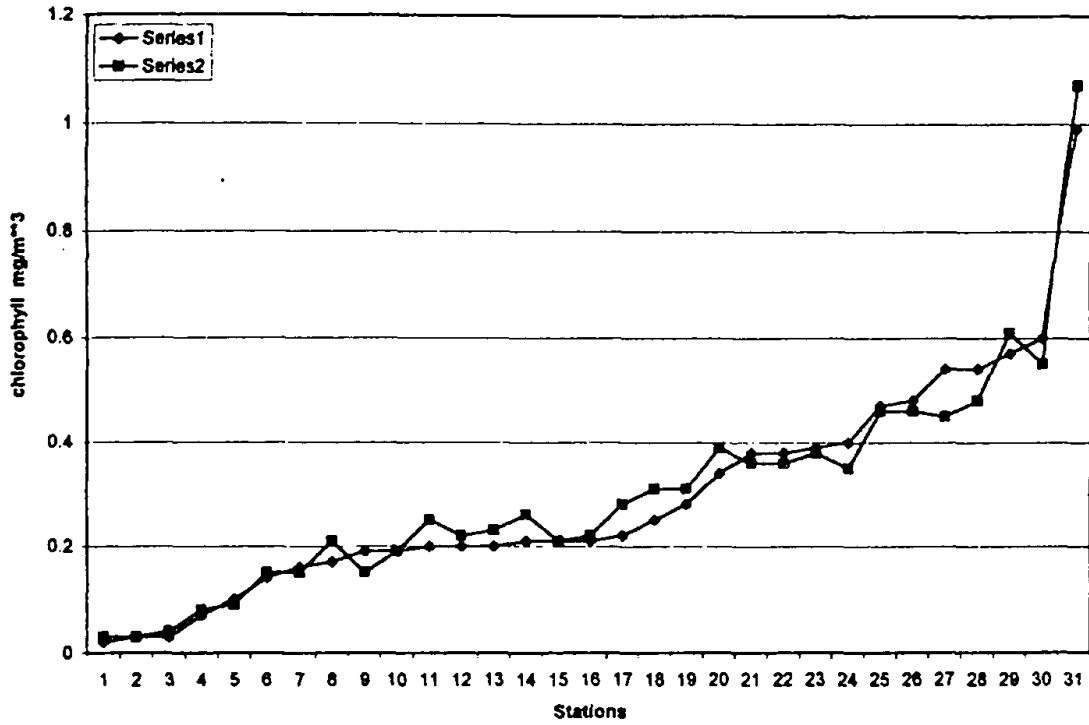


Fig. 3 (A and B). Figures are a graphic representation of performance of SeaWiFS algorithm. Series 1 shows chlorophyll values measured in situ while series 2 shows chlorophyll values estimated from sea leaving radiance. Figure A shows results for matching data points while figure B shows results for the entire dataset.

Table 3: Correlation coefficients and other statistical parameters that describe performance of CZCS and SeaWiFS algorithms

	CZCS Algorithm	SeaWiFS Algorithm
Correlation Coefficient	0.400	0.156
Standard Predictive Error	0.201	0.216
Slope	0.176	0.100
Intercept	0.216	0.255

estimated values of chlorophyll is very well for about 70% of observations while in remaining cases, the agreement is poor. The results further show that the two-factor (SeaWiFS) algorithm has performed better with 74% of chlorophyll values in agreement with estimated ones than the ratio (CZCS) algorithm in which the agreement was 67%. When chlorophyll values were less than 0.05 mg/m^3 , an error of 0.01 mg/m^3 was considered acceptable, while in rest of the cases, chlorophyll values differing within 20% were considered acceptable. Whenever the algorithms failed, computed values were totally unrelated to measured values (see Figs. 2B and 3B).

It is generally expected that chlorophyll retrieval algorithms should work successfully at the sea surface when the upwelling light has barely emerged out of the sea and the spectral signature for chlorophyll contained in it is yet to be contaminated by the earth's atmosphere. This was not the case with our dataset. Both CZCS and SeaWiFS algorithms appeared to fail right at the sea surface in about 30% of cases. When these algorithms failed, chlorophyll content of the sea (see Table 2) was overestimated.

During the sea-truth collection campaign, we frequently encountered cloudy skies. Clouds are known to alter spectral composition of light incident on the sea. As a result, optical measurements are preferably conducted under clear cloud-free skies. In our study however, all measurements of sea-leaving radiation under cloudy skies yielded satisfactory values of chlorophyll. This is probably due to the fact that

ratios of energies contained in different spectral bands of sea leaving radiance are unaffected by cloudy conditions. This observation needs to be verified by examining sufficient radiation data over a pair of stations of identical chlorophyll values, one under cloud while the other under sun. Elsinger and Iverson (1986) have observed change in chlorophyll signal emanating from wind-roughened seas in Atlantic Ocean. During our study, however, we did not notice any significant effect of winds on chlorophyll retrieval within the limited wind speeds (0-12 k) that we encountered. A Monte Carlo model for simulation of sea-leaving radiance from a wind-roughened sea surface has been developed by Sathe and Sathyendranath (1992). Their algorithm does not show appreciable change in chlorophyll signal between calm and rough seas. One needs more observations across a wide spectrum wind speeds to shed more light on the subject.

Both algorithms failed to retrieve acceptable values of chlorophyll in the regions of high sediment load. They overestimated chlorophyll values in most of the cases in the shallow coastal region off Saurashtra coast (northern most locations in Fig. 1). This region receives sediments from the Gulf of Khambat situated on its north-east. The depth of the sea was between 15 and 30 m in this region. Elsewhere in the study area, algorithm failure could not be ascribed to any specific feature such as geographic region or physical state of the sea. Further study on the taxonomy of plankton with reference to the chlorophyll types and other

accessory pigments supported by them might shed more light on the subject.

Errors also arise due to the instruments used in radiation measurement. Operation of LICOR radiometer is a lengthy procedure since it measures radiation only in one direction, either upwelling or downwelling. One needs to lift its sensor out of the sea, invert it and hoist it down again to complete the measurement in the opposite direction. A radiation cast takes about 45 minutes, during which time, the ambient illumination changes. In this situation, values of upwelling and downwelling radiation measured under different illumination at different times enter into computation thus bringing in a built-in error. Use of modern radiometers that measure both upwelling and downwelling radiation simultaneously will eliminate this error. Another source of error is in the method of measurement itself. Upwelling radiation at sea is measured by submerging the sensor a few centimetres below the sea surface. This is done to prevent the surface reflected light from entering into the sensor. Thus, it measures radiation that is still inside the waters, some of which would undergo total internal reflection on reaching the surface from below if sensor were not to obstruct its path. This is different from what satellite measures. Satellite measures radiation that has already left the sea upwards as against radiometers that enter the sea to measure the same. In computations, we consider both quantities as equivalent. Hence, algorithms that work for satellite measurements of radiance are bound to deviate when applied directly for sea leaving radiance. We did not attempt to fine tune regression coefficients and develop indigenous algorithm for our dataset because we consider 42 observations to be inadequate for the purpose. Moreover, the chlorophyll range was limited between 0.02 and 0.99 mg/m³, too restricted for algorithm development.

Both CZCS and SeaWiFS algorithms are of empirical nature and hence region and type specific. They are not nor expected to perform globally on different water types. Their

applicability in computing absolute values of chlorophyll in Indian waters remains largely uncertain. As a result, failure to retrieve chlorophyll in about 30% of cases could be the failure of algorithm itself rather than flawed measurements or extraneous factors.

Conclusion

The two common algorithms, the CZCS and SeaWiFS are not found to work satisfactorily over north Arabian sea to retrieve chlorophyll when applied to radiation data collected by in-situ radiometers. Although they performed well for about 70% of observations, we do not recommend these algorithms for routine retrieval of chlorophyll because the failure in remaining cases could not be attributed to any specific reason. One needs a large data base on simultaneous measurements on upwelling radiation at sea and biological parameters to develop local algorithms, specifically for Arabian sea for use by future ocean colour sensors.

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