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Comparison of Ocean Color Chlorophyll Algorithms for IRS-P4 OCM Sensor Using *in-situ* Data

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ABSTRACT

In-situ chlorophyll concentration data and remote sensing reflectance (R_{rs}) measurements collected in six different ship campaigns in the Arabian Sea were used to evaluate the accuracy, precision, and suitability of different ocean color chlorophyll algorithms for the Arabian Sea. The bio-optical data sets represent the typical range of bio-optical conditions expected in this region and are composed of 47 stations encompassing chlorophyll concentration, between 0.072 and 5.90 mg m^{-3}, with 43 observations in case I water and 4 observations in case II water. Six empirical chlorophyll algorithms [i.e. Aiken-C, POLDER-C, OCTS-C, Morel-3, Ocean Chlorophyll-2 (OC2) and Ocean Chlorophyll-4 (OC4)] were selected for analysis on the Arabian Sea data set. Numerous statistical and graphical criterions were used to evaluate the performance of these algorithms. Among these six chlorophyll algorithms two chlorophyll algorithms (i.e. OC2 and OC4) performed well in the case I waters of the Arabian Sea. The OC2 algorithm, a modified cubic polynomial function which uses ratio of R_{rs}490 nm and R_{rs}555 nm (where, R_{rs} is remote sensing reflectance), performed well with r^2=0.85; rms =0.15. The OC4 algorithm, a four-band (443, 490,510, 555 nm), maximum band ratio formulation was found best on the basis of statistical analysis results with r^2=0.85 and rms=0.14. Both OC2 and OC4 algorithms failed to estimate chlorophyll in *Trichodesmium* dominated waters. The OC2 algorithm was preferred over OC4 algorithm for routine processing of the OCM data to generate chlorophyll-a images, as it uses a band ratio of 490/555 nm and atmospheric correction is more accurate in 490 nm compared to 443 nm band, which is used by OC4 algorithm.

Introduction

Phytoplankton play an important role in determining the color of seawater. The primary photosynthetic pigment of oceanic phytoplankton is chlorophyll-a. Therefore its estimation is useful in the study of ocean primary production, fisheries research and the study of biogeochemical cycle (Scientific Committee on Oceanic Research (SCOR), 1987; Falkoski,

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1994). Satellite ocean colour data provide us with the practical means for monitoring the spatial and seasonal variations of near surface phytoplankton. After the pioneer CZCS mission (Clarke et al., 1970; Evans and Gordon, 1994), there has been an emergence of new generation ocean color sensors, such as SeaWiFS of NASA (Hooker et al., 1992), OCTS of NASDA (Fukushima et al., 2000), IRS-MOS of DLR, Germany (Zimmermann,1995) and IRS-OCM of India (Navalgund and Kiran Kumar, 1999). These new sensors have improved capabilities to precisely estimate seawater constituents. With the improved sensors, improvements in bio-optical algorithms are also required for making accurate estimates of chlorophyll pigment from satellite data. Such improvements are expected to enhance the accuracy of ocean phytoplankton biomass assessments.

Numerous bio-optical algorithms have been developed to estimate chlorophyll a (C) or chlorophyll a + phaeopigments ([C +P]) concentration from ocean radiance data. Most of these are empirical relations derived by statistical regression of radiance versus chlorophyll. Advances have been made towards the development of model-based algorithms, which uses knowledge of the marine light field and optical properties of seawater constituents (Sathyendranath et al., 1989; Bricaud et al., 1995). However, despite these advances, the limited number of in-situ measurements combined with satellite data on the same day has affected the development and evaluation of accuracy and precision of ocean color chlorophyll algorithms.

The Ocean Colour Monitor (OCM) onboard the Indian Remote Sensing Satellite (IRS)-P4 is a second generation ocean color sensor with eight spectral bands located at 412, 443, 490, 510, 555, 670, 765 and 865 nm. The sensor has narrow spectral bands, high signal to noise ratio, swath of 1420 km and two days temporal resolution (Navalgund and Kiran Kumar, 1999). In order to exploit OCM data for quantitative estimates it was essential to narrow down the search for a suitable bio-optical chlorophyll a algorithm, which works well in the oceanic waters of the Arabian Sea. The development of a regional bio-optical algorithm needs a large number of in-situ measurements; it was not feasible to construct a local algorithm with a limited data set. In the absence of this large data set it was decided to evaluate existing chlorophyll algorithms for use in the Arabian Sea.

The results of the evaluation of six bio-optical algorithms tested using a data set obtained in the Arabian Sea during six ship campaigns during April 1996 to April 2000 are discussed in the present study. Fig. 1 shows the spatial distribution of the sampling stations in the Arabian Sea. The accuracy and suitability for chlorophyll estimation by OCM sensor have been discussed.

Chlorophyll Algorithms

O'Reilly et al. (1998) has carried out a comprehensive evaluation of a large number of semi-analytical and empirical bio-optical algorithms for data collected from different sources and different global locations during SeaWiFS Bio-Optical Algorithm Mini-workshop (SeaBAM). The data set used is known as the SeaBAM bio-optical data archive. Based on their analysis it was found that most of the empirical algorithms performed better than semi-analytical algorithms. Among the empirical algorithms, cubic polynomial formulations such as Ocean Chlorophyll 2 (OC2) and Ocean Chlorophyll 4 (OC4) models were considered to be the best among all the empirical models. In the present study we have selected the six best empirical equations for evaluation using Arabian Sea bio-optical data set. The selection of these algorithms was based on the results of the comparative analysis of O'Reilly et al. (1998). Only chlorophyll a algorithms are selected and total pigment algorithms were omitted from our analysis. It was also decided not to use regional algorithms like the one constructed from CalCOFI (California Cooperative Oceanic

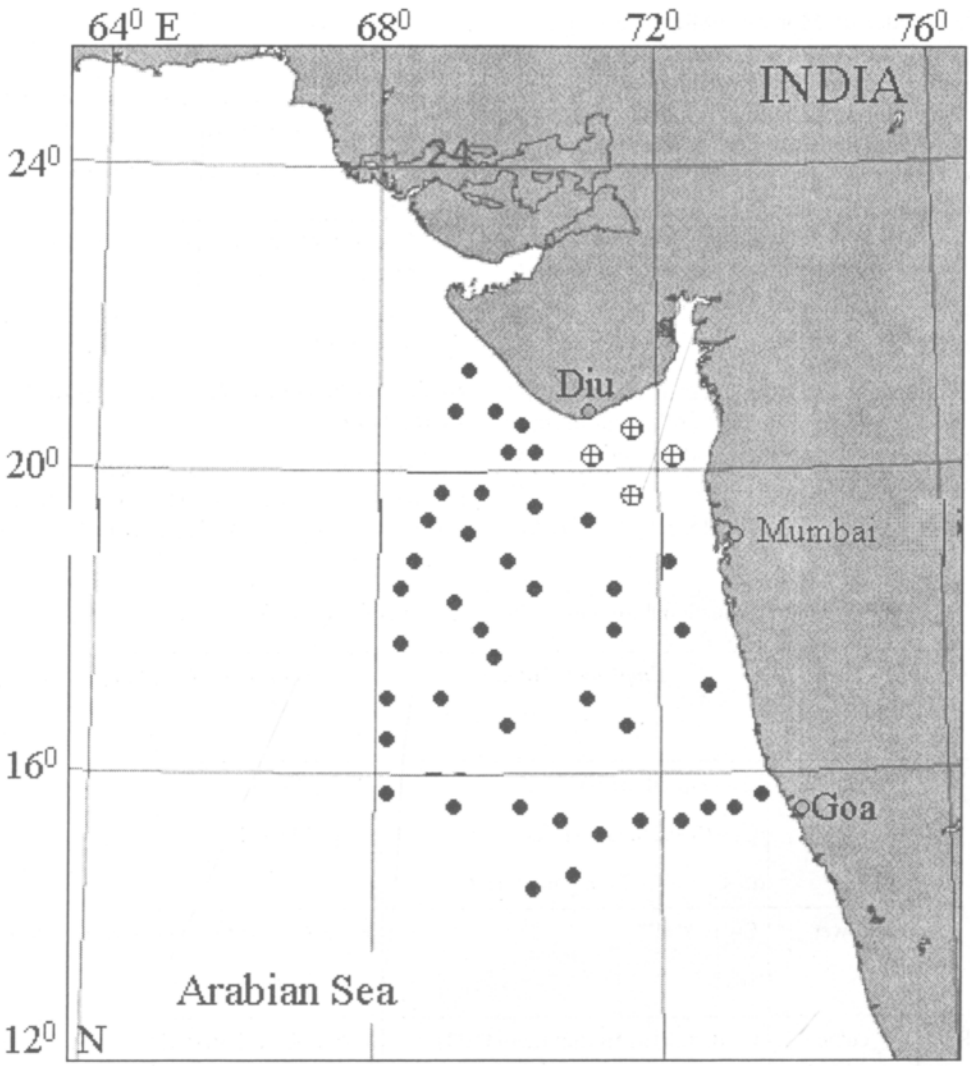

Fig. 1. The figure shows station locations in the Arabian Sea where bio-optical measurements were made during the sea-truth collection. The solid circles show stations in clear case I waters and crossed circles show stations in case II waters.

Fisheries Investigations) data sets (Mitchell and Kahru, 1998). Table 1 shows the functional form of the algorithms used.

The Aiken hyperbolic model estimates C by the combination of a hyperbolic function up to 2 mg m^{-3} with a power function at higher concentrations (Aiken et al., 1995). The OCTS-C model is a power-law function, which uses the sum of normalized water leaving radiance (L_{wn}) in 520 nm and 565 nm over 490 nm to estimate C (O'Reilly et al., 998). The POLDER algorithm is considered empirical because it is based on a simple equation relating C to a band ratio, although the equation was actually derived from the use of a modified version of the semi-analytical model of Morel (1988). The Morel 3 algorithm relates $R_{rs}443$ nm / $R_{rs}555$ nm to C and uses a cubic polynomial equation, where R_{rs} is remote sensing reflectance (O'Reilly et al., 1998). The OC2 algorithm uses a modified cubic polynomial equation and relates C to $R_{rs}490$ nm / $R_{rs}555$ nm. The OC4 algorithm uses a maximum band ratio of $R_{rs}443$ nm, $R_{rs}490$ nm, $R_{rs}510$ nm to $R_{rs}555$ nm in a modified cubic polynomial equation (O'Reilly et al., 1998).

Data Used

To evaluate the performance of chlorophyll algorithms an in-situ data set collected in the Arabian Sea was used. Such a data set has the following attributes:

1. Contain R_{rs} or L_{wn} at or close to the OCM visible wavelengths
2. In-situ chlorophyll a concentration associated with the stations from which R_{rs} or L_{wn} were derived
3. A wide range of chlorophyll a concentration values
4. D not contain data used for the development of the algorithm
5. Same data set should be used to evaluate all the algorithms.

Radiometric Data: Measurements and Processing

Sea truth collection campaigns were conducted in the Arabian Sea onboard the Research Vessel ORV-Sagar Kanya as a part of

Table 1: Functional form of the bio-optical algorithms used in the study

Algorithm	*Type*	*Empirical Equation*	*Band Ratio (R), Coefficients (a)*
Aiken-C	Hyperbolic +power	C_{21}=exp(a0+a1*ln (R)) C_{23}=(R+a2)/(a3 +a4*R) C=C_{21}; if C<2.0 mg m^{-3} then C=C_{23}	R=$L_{wn}490$/ $L_{wn}555$ a= [0.745,-2.252]
OCTS-C	power	C= $10^{(a0+a1*R)}$	R=log((Lwn520 +Lwn565)/Lwn490) a=[-0.55006,3.497)
POLDER	cubic	C=10^(a0+a1*R+a2*R2+a3*R3)	R=log(Rrs443/Rrs565) a=[0.438,-2.114,0.916,-0.851]
Morel-3	cubic	C=10^(a0+a1*R+a2*R^2+a3*R^3)	a=[0.20766,-1.828,0.75,-0.739]
OC2 ver.-4	Modified cubic	C=10^(a0+a1*R+a2*R^2+a3*R^3)+a4	R=Log(Rrs490/Rrs555); a={0.319,-2.336,0.879,-0.135,-0.071}
OC4 ver.-4	Modified cubic	C=10^(a0+a1*R+a2*R^2+a3*R^3)+a4	R=Log(Rrs443>Rrs490>Rrs510/Rrs555) * a={0.366,-3.067,1.93,0.649,-1.532}

*Log refers to logarithm to the base 10, ^ refers to the exponentiation.

IRS P3 MOS and IRS P4 OCM validation experiments during April 1996 to April 2000. The study area within the Arabian Sea covered regions between 14^0N and 68^0E, encompassing a total number of 47 stations in case I and case II waters. The spatial distribution of the sampling stations has been shown in Figure 1. Various optical and biological measurements were carried out during these cruises. The measurements include the upwelling $[E_u(\lambda,z)]$ and downwelling irradiance $[E_d(\lambda,z)]$ and the upwelling radiance $[(L_u(\lambda,z)]$ at equidistance depths up to 50 m in open and coastal ocean waters. The optical data was collected as per the SeaWiFS protocols (Muller and Austin, 1995).

The downwelling irradiance just below the sea surface $[E_d(0^-,\lambda)]$ and the upwelling irradiance just below the sea surface $[E_u(0^-,\lambda)]$ were calculated by performing a least squares fit for the statistical regression of z versus $\log(E_d)$ and $\log(E_u)$, respectively, and projecting the best fit curves to zero depth. The water leaving radiance, $L_w(\lambda)$, was then calculated using the following equation:

$$L_w(\lambda) = E_u(0^-,\lambda).(1-\rho_u)/(n^2.Q)$$

where, ρ_u is the Fresnel reflectance for upward radiance, n is the refractive index of the sea water and Q is the ratio of underwater irradiance to the radiance. The remote sensing reflectance, $R_{rs}(\lambda)$, the ratio of water leaving radiance to the downwelling irradiance just above the sea surface $E_d(0^+,\lambda)$, was computed using following equation:

$$R_{rs}(\lambda)=L_w(\lambda)/E_d(0^+,\lambda)$$

where $E_d(0^+,\lambda)$ was calculated from E_d $(0^-,\lambda)$, using the following equation:

$$E_d(0+,\lambda)= E_d(0^-,\lambda)/0.96$$

where, 0.96 is the transmittance across the air-sea interface, assuming a normal incidence angle (Smith and Baker, 1978).

In-Situ Chlorophyll *a* Data

The fluorometric method was used for quantitative estimation of chlorophyll-a and phaeopigments. Water samples obtained from Conductivity, Temperature and Depth (CTD) casts were collected into polyethylene bottles. Chlorophyll-a was determined by filtering one litre of water sample using 47 mm GF/F Millipore filters (nominal pore size 0.7 μm). Filter papers were folded and dipped in 10 nml of 90% acetone in a dark freezer for 24 hours to extract the chlorophyll. Further analysis for the extraction of chlorophyll-*a* was conducted as per the JGOFS protocols. Surface chlorophyll-a values ranged between 0.072 to 5.9 mg m^{-3} for various stations.

Evaluation criteria

The chlorophyll algorithms were evaluated using statistical and graphical criteria for C estimated by the models, and *in-situ* C. A regression analysis was performed between modeled and *in-situ* measured chlorophyll-a concentration values. Statistics such as regression slope and intercept, coefficient of determination (r^2) and root mean square error (RMS) provide a numerical index of the model performance and graphical criteria such as scatter analysis provides indication on the non-linear behavior of the fit. The RMS analysis provides a useful estimate of the precision between model and *in-situ* data. The RMS statistics for the comparison of the two algorithms was generated using the following formula:

$$RMS = \sqrt{\frac{N\Sigma(\log(Xi_{mod}...) - \log(Xi_{meas}))^2}{n}}$$

where, X_i is chlorophyll-a concentration for a station i, and n is the total number of stations in the data set. The performances of the algorithms were evaluated on the basis of a standard evaluation criterion. According to these criteria the slope of the regression analysis should be close to 1, intercept value should be close to zero, coefficient of determination (r^2) should be more than 0.80 with and RMS error less than 0.185.

Table 2: Summary of the statistical results of algorithms evaluation.

Algorithm	*N*	*Intercept*	*Slope*	R^2	*RMS*	*Negative Estimates*
Aiken-C	43	-0.62	0.64	0.55	0.27	none
POLDER-C	43	-0.164	1.34	0.70	0.45	none
OCTS-C	43	0.070	0.73	0.64	0.30	none
Morel-3	43	-0.005	0.82	0.60	0.32	none
OC2 v.4	43	-0.10	0.89	0.85	0.15	none
OC4 v.4	43	-0.11	0.87	0.85	0.14	none

Results and Discussion

Using the above described procedure; a regression analysis was performed between log transformed chlorophyll estimated using the six chlorophyll algorithms and log transformed *in-situ* measured chlorophyll-a values. The total data set for this study was 47 stations, which also included four stations of high chlorophyll concentration owing to the presence of *Trichodesmium* cynobacteria bloom. All the six algorithms overestimated the chlorophyll-a pigment value at stations corresponding to waters rich in *Trichodesmium*. However, after the removal of these 4 stations from the data sets and considering only case 1 waters in the Arabian Sea, a better agreement was found between modeled and measured pigment concentration values for all the six algorithms. Table 2 shows the statistics of the regression analysis. Fig. 1 shows the relationship between *in-situ* chlorophyll and chlorophyll values estimated using six different algorithms in case I waters.

Out of these six algorithms four algorithms namely Aiken-C, POLDER-C, OCTS-C and Morel-3 performed poorly in comparison to OC-2 and OC-4 algorithms. Only two algorithms OC-2 and OC-4 could meet the requirements of the evaluation criteria. These two algorithms performed reasonably well in the chlorophyll-a concentration range of 0.072 to 2.5 mg m^{-3}. The POLDER-C algorithm under estimated lower chlorophyll concentration values, while OCTS-C algorithm overestimated the smaller concentration of chlorophyll-a. The Morel-3 algorithm was found good for overall range of chlorophyll-a concentration, however it produced large scatter and a relatively larger RMS error. The OC-2 and OC-4 algorithms produced better results with good coefficient of determination (r^2) value of 0.85. However, it was found that both these algorithms failed for waters rich in marine cynobacterium *Trichodesmium* bloom. Further, the OC-2 algorithm was preferred to the OC-4 algorithm for the OCM sensor based chlorophyll-a retrieval, because it uses the 490/555 nm, band ratio and the atmospheric correction accuracy is much better in the 490 nm compared to 443 nm band of OCM.

Conclusion

The results of this study indicate that the

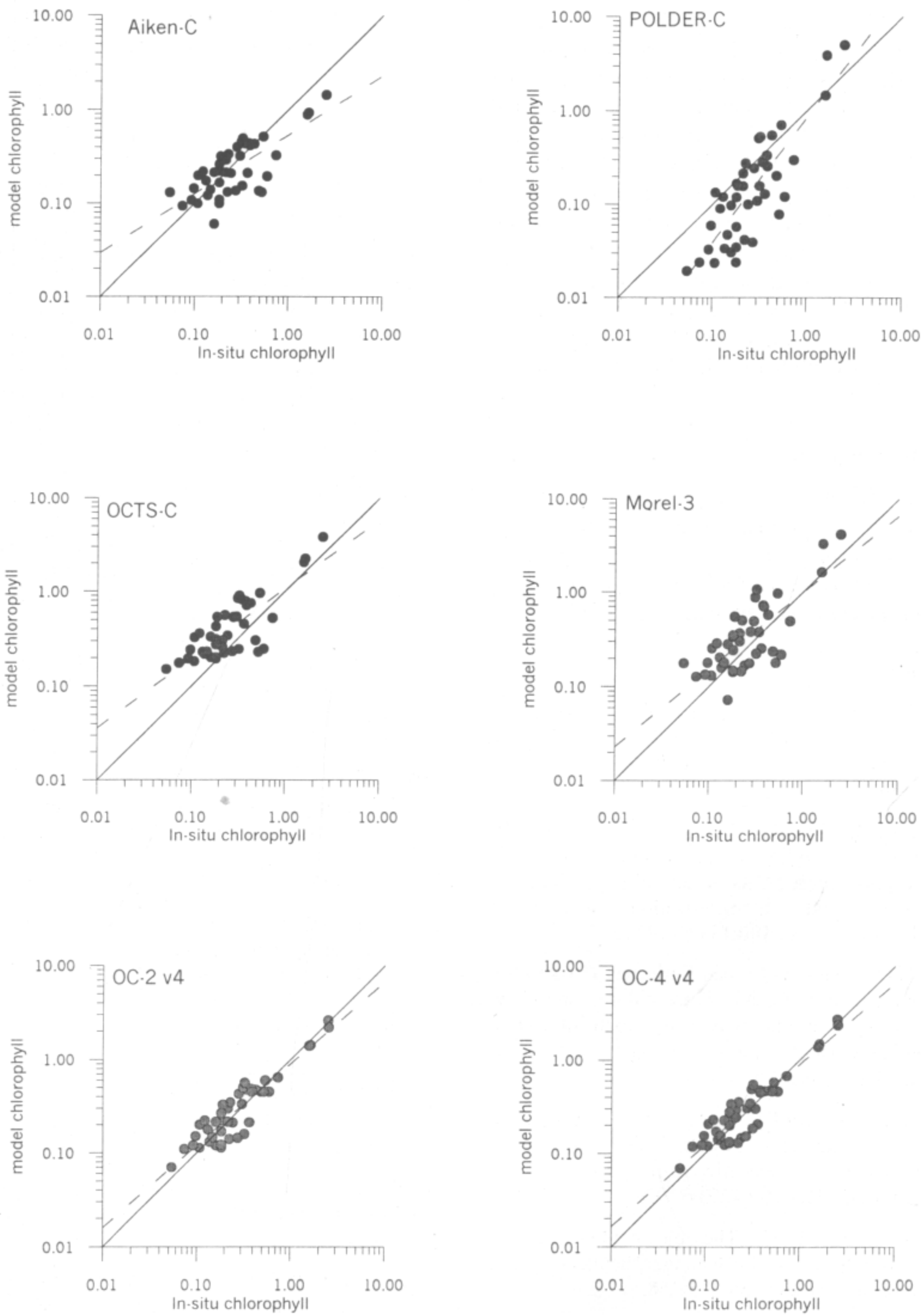

Figure 2. Comparison between in-situ chlorophyll and modeled chlorophyll using six different chlorophyll algorithms for the Arabian Sea data sets.

OC2 and OC4 bio-optical algorithms are capable of determining quantitative estimates of surface chlorophyll-a, using remotely sensed optical data in the Arabian Sea. Both the algorithms have been independently validated and found to give reasonably good results in the case I waters of the Arabian Sea, however both algorithms have failed in case II sediment laden waters of the Gulf of Khambat and waters with the cynobacterium *Trichodesmium* bloom. Among the OC2 and OC4 algorithms, OC2 was superior in this study area and also more most suitable for operational use with the IRS-P4 OCM satellite data.

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