Sea truth validation of SeaWiFS ocean colour sensor in the coastal waters of the Eastern Arabian Sea

Elgar Desa*, T. Suresh, S. G. Prabhu Matondkar and Ehrlich Desa

National Institute of Oceanography, Dona Paula, Goa 403 004, India

In this paper we report bio-optical measurements made during an ocean colour validation cruise *SK 149C* in November 1999 of the research vessel *Sagar Kanya* in the coastal waters of the Eastern Arabian Sea. The chlorophyll concentration in these waters was in the range 0.2 to 4 mg/m^3. Although the match-ups between *in situ* and satellite data from SeaWifs were sparse, it indicates that direct application of the standard SeaWifs algorithm – the OC2-V4 algorithm – in the coastal waters of the Arabian Sea will *underestimate* chlorophyll by up to 30%. Comparison of our *in situ* normalized water-leaving radiance [*Lwn*] and chlorophyll measurements at sea with that derived from the SeaWifs colour sensor shows that SeaWifs overestimates both *Lwn* and chlorophyll. Various authors have earlier reported under and over estimation of SeaWifs water-leaving radiances, speculated as arising from variable errors when correcting atmospheric effects in coastal regions. These errors are produced most probably by absorbing aerosols and also from increases in water-leaving radiance caused by enhanced particle backscatter effects from sea water constituents other than chlorophyll. Further studies are required to resolve the problem of validating satellite sensors in coastal waters.

THE spatial and temporal variabilities in the bio-optical and physical properties of coastal waters present unique challenges to their study by satellite colour sensors such as Sea-viewing Wide Field-of-view Sensors (SeaWifs) and the Ocean Colour Monitor (OCM) on the IRS-P4 satellite. Unlike open ocean waters in which chlorophyll is the dominant constituent affecting optical properties, coastal waters contain a mix of chlorophyll, suspended sediments from river run-off and dissolved organic matter. This results in a more complex water-leaving signal reaching the satellite sensor.

The first step in the retrieval of sea water constituents is the validation of the marine signal reaching the satellite sensor through comparisons with *in situ* measurements made during a satellite pass. We therefore present here the biological and radiometric measurements made at sea

and explore the relationships between spectral radiance and chlorophyll. The pigment algorithm of choice for this area of observation is also discussed.

Measurements were made at 24 stations, though only 4 match-up stations with SeaWifs were found to be useful for inter-comparisons with *in situ* data. Such a low match-up ratio is expected since environmental perturbations from clouds, ship-shadows, waves and sky conditions limit the occasions when conditions of a satisfactory nature are met. The differences observed between water-leaving radiance and chlorophyll estimated from SeaWifs signal and our measurements are discussed in the conclusions.

Data

Figure 1 shows the track of the validation cruise *149C* of ORV *Sagar Kanya*, undertaken between 15 and 29 Novem-
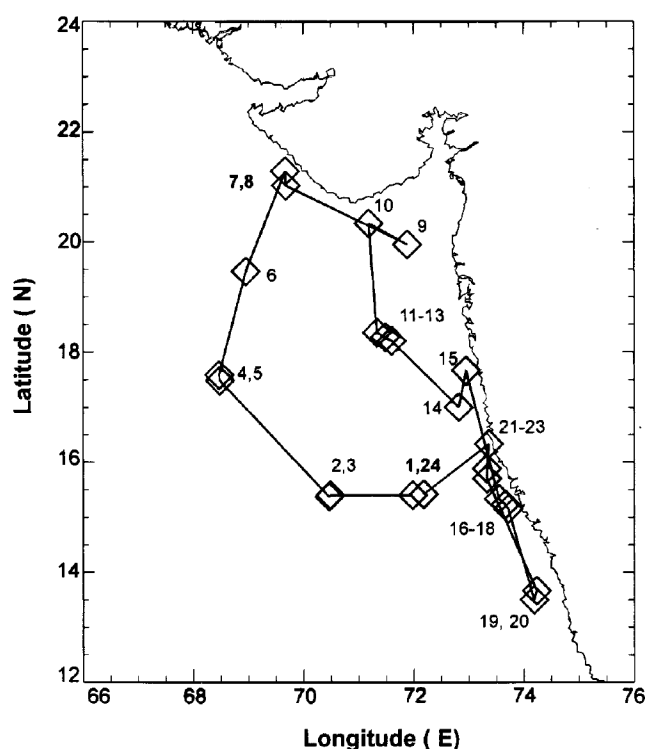

Figure 1. Cruise track adopted by ORV *Sagar Kanya* during *SK 149C* in November 1999.

*For correspondence. (e-mail: elgar@csnio.ren.nic.in)

ber 1999. The cruise track was proposed after examining the chlorophyll fields from past SeaWifs imageries of November/December 1998 and was closely followed for this cruise. Based on the chlorophyll fields, it was decided to cover a few open ocean stations with low chlorophyll content and focus more on coastal stations with higher chlorophyll content.

A summary of 19 bio-optical stations out of 24 stations is shown in Table 1. We have made a qualitative assignment of station type as '*coastal*', '*open ocean*' or '*hybrid*' by basing the assignment on the generic spectral shapes of the normalized water-leaving radiance [*Lwn*] shown in Figure 2. Open ocean locations have maximum radiances at 412 nm, coastal stations develop a band structure with a peak near ~ 510 nm and hybrid stations have a shape that borrows features from both types. Useful optical casts without ship shadow were made at 11 coastal stations, 5 open-ocean, and 3 hybrid open ocean/coastal stations. The remaining stations were rejected as the data were adjudged to be unreliable due to poor sea or sky conditions arising from overcast light fields, variable, but continuous wind-producing swells or strong surface currents that would make a cast unreliable. Table 1 also lists the satellite penetration depth, Z_{90} at 490 nm derived from the diffuse attenuation coefficient[1]. The depth-averaged chlorophyll-*a* concentration over Z_{90} and meta data on the sky and sea states at each station are also tabulated.

The SeaWifs sensor had been switched off between 16 and 19 November 1999 as a precautionary safety measure from the passing Leonids meteorites cluster during this period. The cruise track had occupied open ocean stations 1 to 5 during this event. Acceptable match-ups between *in situ* measurements and SeaWifs data were obtained at stations 6, 10, 20 and 22, corresponding to 1 open ocean and 3 coastal stations (see Table 1).

In general, Z_{90} depths of ~ 18 m at open ocean stations were nearly double those measured in coastal and hybrid stations. Chlorophyll concentrations were often several orders of magnitude higher near the coast than in open seas. At coastal stations 8, 9 and 10, we encountered temperature inversion of the thermocline, while at stations 17 and 19, we recorded intense physalia (*Portuguese man-of-war*) blooms. Such events are missed completely by satellite-based sensors as they appear invariably in the early part of the day, often disappearing by noon when a satellite overpass takes place.

In situ bio-optical measurements

Chlorophyll method

Chlorophyll-*a*, phaeopigments and carotenoids were estimated from the water sampled by GO-FLO bottles attached to the conductivity–temperature–depth rosette. The sampling depths were decided by the shape of the thermocline or the natural fluorescence, recorded by Sea-Bird's Profiling CTD or Biospherical Instruments' Natural Fluorescence Radiometer, respectively.

Table 1. Station characteristics during *SK 149C* cruise

Date	Station no.	Station depth (m)	Station type*	Z_{90} (m)	⟨Chl⟩ over Z_{90} (mg/m³)	Condition at station
17 November 1999	2	3350	Open ocean	18 20	0.195	Clear sky
18 November 1999	3	3850	Open ocean	19 20	0.341	Clear sky
19 November 1999	4	3500	Open ocean	17	0.304	Clear sky
19 November 1999	5	3500	Open ocean	20	0.405	Clear sky
20 November 1999	6	2700	Open ocean	14	0.324	Cloudy sky, blue-green sea; *SeaWifs match-up*
21 November 1999	8	45	Coastal	7	0.891	Cloudy sky, green sea, temperature inversion
22 November 1999	9	60	Coastal	10	0.344	Partially cloudy, temperature inversion
22 November 1999	10	45	Coastal	7, 9	0.558	Cloudy sky, green sea, temperature Inversion; *SeaWifs match-up*
23 November 1999	11	75	Coastal	11	0.730	Cloudy sky, green sea
23 November 1999	12	85	Coastal	11, 12, 13	0.668	Scattered clouds, green sea
24 November 1999	14	60	Coastal	7	1.497	Thick clouds, calm sea
24 November 1999	15	45	Coastal	7	1.966	Cloudy sky, green calm sea
25 November 1999	16	42	Coastal	7	1.160	Hazy sky, green waters
25 November 1999	17	30	Hybrid	12 9	0.688	Scattered clouds, green calm sea
25 November 1999	18	32	Hybrid	10 10	2.555	Scattered clouds, green calm sea
26 November 1999	19	40	Hybrid	11	0.485	Intense Physalia bloom
26 November 1999	20	40	Coastal	10	0.384	Sunny sky; Radiometer time series; *SeaWifs match-up*
27 November 1999	21	24	Coastal	5	4.060	Calm and green sea
27 November 1999	22	35	Coastal	6	0.773	Calm and green sea; *SeaWifs match-up*

Z_{90}, Satellite penetration depth.
⟨Chl⟩, Chlorophyll-*a* concentration.

Water samples were pre-filtered through a nylon mesh (0.3 mm) to remove macro-zooplankton and larger particles. Subsamples (1.5 to 2.5 l) were filtered again through Whatman GF/F glass microfibre filters of mesh size 4 micron. After filtration, pigments were extracted from the filters by grinding with a glass homogenizer in 90% acetone solution. The fluorescence of the supernatant was measured before and after acidification using a Turner Designs fluorometer which was earlier calibrated with Chlorophyll Standards (Sigma Chemicals) in 90% acetone.

Acidification was done with 0.2 ml of 1M HCl in 10 ml of acetone extract. Chlorophyll-a and the phaeopigments are the pigments that are sensitive to acidification. Deep-frozen samples were used to estimate carotenoids on a spectrophotometer. A duplicate set of samples was kept aside for measurements on a spectrophotometer at the shore-based laboratory, as a check on the fluorometric method. The results from the two techniques agreed to better than 2%.

Radiometric Lu and Ed

Conventional radiometers are normally lowered from a hydrographic winch, often fairly close to the side of the ship and on its sunny side. Gordon[2] has shown that this method of measurement is contaminated by the perturbing effect of the ship on the downwelling irradiance field leading to errors of 1–2%, for clear skies with the sun within ± 45 degrees of the beam of the ship. Errors of up to 10% occur if the sun is off the bow or stern of the ship and wavelength-independent errors of up to 20 to 30% are possible in overcast skies.

In order to minimize these errors, in-water radiometric measurements of upwelling radiance [Lu] and downwelling irradiance [Ed] at the SeaWifs/OCM wavebands of 412, 443, 490, 510, 555 and 670 nm (an additional 683 nm was included to detect fluorescence in the upwell-
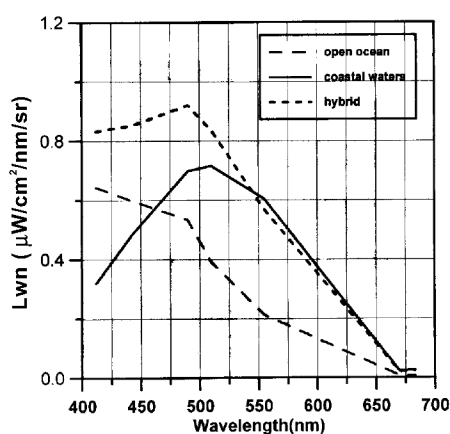

Figure 2. Typical normalized water-leaving radiance spectra (nLw or Lwn) at SeaWifs wavelengths for three station types encountered during the cruise, namely open ocean (small dashes), shallow coastal station (solid line) and a hybrid (large dashes).

ing field) were made with a free-fall profiling radiometer (Satlantic Inc.). Using Monte Carlo simulations, Gordon and Ding[3] have estimated that a safe distance of [$\sin(48.4°)/Kd$] avoids ship-shadow effects. This works out to ~ 5 m for most of the stations that we occupied. Our own estimates based on the length of cable paid out are ~ 15 m as the initial drop-off point of the profiler, well clear of the ship and ship-shadow effects.

A separate sky-viewing reference radiometer mounted on the forecastle deck of the ship, but having only 7 separate Ed sensors on an end-cap of the casing, measured Ed at the same SeaWifs/OCM wavebands that are on the in-water unit. Both wet and dry radiometers connect to a deck control unit that synchronizes the acquisition of the 21 channels of data, receives the data streams and retransmits them to a log-in computer.

Normalized water-leaving radiance (Lwn)

Lwn has a spectral nature and ideally is that radiance which would exit the sea surface if the sun were at the zenith and if the atmosphere were absent[4]. For consistency with the methodology adopted by O'Reilly et al.[5] for pigment algorithms, we express Lwn in terms of 'above sea surface' values of $Lu(0^+)$ and $Es(0^+)$, using the approximation $Lu(0^+) = 0.544Lu(0^-)$, where $Lu(0^-)$ is the 'below sea surface' water-leaving radiance measured by the profiling radiometer, and $Es(0^+)$ is the measured downwelling irradiance from the reference sky-viewing radiometer above the sea surface. The Lwn definition for any wavelength is:

$$Lwn = F_0[Lu(0^+)/Es(0^+)]. \qquad (1)$$

F_0 is the mean extra-terrestrial irradiance at mean earth–sun distance[6] at a given wavelength. This definition permits us to compare Lwn spectra at different locations on the earth's surface and is independent of sun angle or time of day.

A further cross check on the irradiance values [Ed] of the in-water profiler data just below the sea surface was made by using the independent sky-viewing radiometer Es values, and forward-propagating these values through the air–water interface for comparison with the in-water values just below the sea surface. We recommend this check for all satellite validation work. If the surface $Es(0^+)$ measurements are not available, then the approximation $Ed(0^-) = 0.96Ed(0^+)$ from Smith and Baker[7] could be used to translate the profiler $Ed(0^-)$ to $Ed(0^+)$. The subsurface values $Lu(0^-)$ and $Ed(0^-)$ were determined from vertical profiles of radiometric casts by first estimating the attenuation coefficients $K(Lu)$ and $K(Ed)$ of Lu and Ed, respectively, using the least squares fit method of Smith and Baker[8] to log transformed data of Lu and Ed, respectively.

At most stations in this cruise, the maximum Lwn occurring in the blue was typically $< \sim 1 \ \mu W/cm^2/nm/sr$. Lwn values at 670 nm and 683 nm are similar in magnitude, but a factor of ~ 30 less than the maximum Lwn, with no detectable chlorophyll fluorescence structure seen in the two red channels at 670 nm and 683 nm at all stations.

Remotely sensed reflectance pigment algorithm

The vertical casts of Lu and Ed light fields 'extrapolated to the sea surface' and the in situ chlorophyll-a concentration measured at stations in the cruise are used to construct a pigment–radiance relationship. The remotely sensed reflectance (Rrs) defined below (see eq. (2)) follows the convention adopted by O'Reilly et al.[5] for the SeaBam data set, where Rrs is expressed in terms of above the surface quantities:

$$Rrs = Lu(0^+)/Es(0^+). \qquad (2)$$

The variation of the dimensionless ratio $[Rrs(490)/Rrs(555)]$ with chlorophyll-a concentration (mg/m^3) integrated over the penetration depth Z_{90} $[= 1/Kd(490)]$ seen by a ocean colour satellite sensor is shown in Figure 3. The most recent standard NASA algorithm[5] (www.seawifs.gsfc.nasa.gov/SEAWIFS/RECAL/Repro3) Ocean Chlorophyll-2 (OC2-V4) has been drawn into (but not fitted to the data points) Figure 3 and takes the form:

$$Chl\_a = 10^X - 0.071, \qquad (3)$$

10.0 ─

Rrs (490/555)

In-situ data
Ours
OC2 ver4

1.0 ─

0.1 ─

0.0   0.1   1.0   10.0   100.0
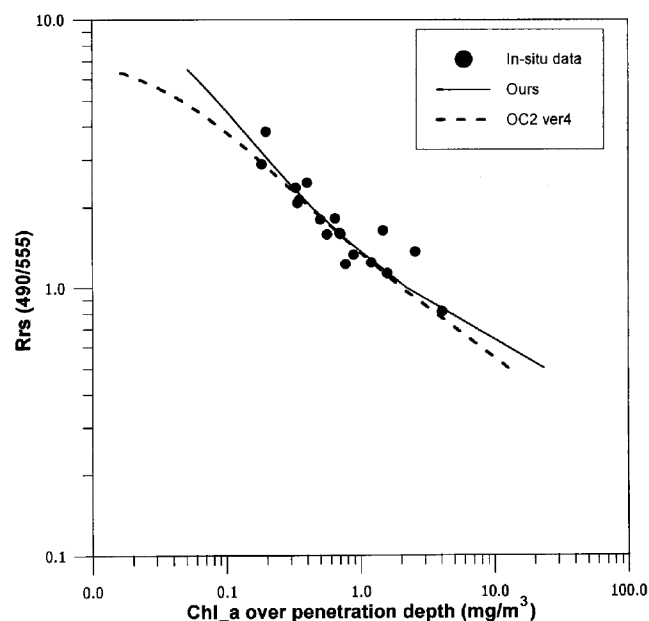
Chl_a over penetration depth (mg/m³)

Figure 3. Measured data values of remotely sensed reflectance ratio for 490 nm to 555 nm against in situ chlorophyll integrated over the satellite penetration depth ($\sim 37\%$ light level). The standard SeaWifs algorithm has been drawn in as a dashed line, the solid line is an actual fit of the modified standard algorithm to the data points.

where $X = 0.319 - 2.336R - 0.879R^2 - 0.135R^3$, and $R = \log_{10} [Rrs(490)/ Rrs(555)]$.

A polynomial fit like eq. (3) to actual data of Figure 3 can be obtained by least squares method to obtain a set of new coefficients in the standard algorithm, and a modified algorithm of similar form (see Figure 3):

$$Chl\_a = 10^X - 0.059, \qquad (4)$$

where $X = 0.353 - 2.719R + 1.960R^2 - 0.7327R^3$, and $R = \log_{10} [Rrs(490)/Rrs(555)]$.

In order to quantify the visual log–log fits to the data of Figure 3, we have regressed the algorithmic estimates of chlorophyll given in eqs (3) and (4) against the measured chlorophyll values. A least squares linear regression of the OC2-V4-derived chlorophyll (see eq. (3)) against in situ chlorophyll produces a fit with slope 0.80, a coefficient of determination 0.91 and standard error of estimate, $\sigma = 0.24$, as in Figure 4 a. The regression of chlorophyll from the modified algorithm (see eq. (4)) with in situ chlorophyll produces a marginally closer fit with slope 0.96, coefficient of determination 0.93 and a standard error of estimate, $\sigma = 0.26$, as in Figure 4 b. The Root Mean Square Difference (RMSD) (see definition below) for the standard and the modified algorithms from the in situ values are 27% and 26%, respectively, indicating near similar capability in estimating chlorophyll remotely to this accuracy. The modified algorithm fit of Figure 3 is valid for Chl_a values in the range $0.1 \ mg/m^3$ and $4 \ mg/m^3$ but will change as more data are available over the full dynamic range of chlorophyll.

The less than unity slope of the regression lines in Figure 4 a shows that use of the standard algorithm (OC2-V4 or the earlier OC2) will result in an under-estimation of chlorophyll. The standard algorithm will report a reduced estimate of chlorophyll concentration at the same experimental Rrs ratio. Conversely, over-estimation of chlorophyll will occur if the experimental Rrs ratio were smaller than the algorithm ratio at a given C value.

The $Rrs(\lambda)$ reflectance at wavelength λ is expressed as a function of the coefficients for backscatter (b_b) and the absorption (a) by[9]:

$$Rrs(\lambda) \sim f[(b_b)/(b_b + a)]. \qquad (5)$$

We can expect maximum values of Lwn and the Rrs ratio at 490 to 555 nm wavelengths in these spectra when measured in coastal waters (see Figure 2, for example), where it is known[4] that sub-micron particles in suspended sediments, phytoplankton and auxiliary pigments, detrital particle fractions and dissolved coloured substances will act to increase the magnitude of backscatter coefficients b_b at 555 nm and 490 nm – the part of the visible spectrum where the absorption coefficients of sea water dip to a minimum low. Regressions with open ocean stations included, show that underestimation of chlorophyll by the

standard algorithm is reduced to RMSD of ~ 20%. As coastal stations are included in the regressions, the slope of the best fit is increasingly less than 1 (as in Figure 4 a) by larger underestimates of chlorophyll arising from increases in the Rrs ratio through particle backscatter.

Vertical structure of Rrs

Selected profiles of $Rrs(490)/Rrs(555)$ and $Rrs(443)/Rrs(555)$ are shown in Figure 5, alongside the chlorophyll

profile measured at the same station. Both Rrs ratios have peaks that coincide with a change in the chlorophyll gradient. The vertical profile of Kd, the attenuation coefficient of the irradiance field Ed, is also known to mimic the chlorophyll field closely[10,11]. The correlation of Rrs with chlorophyll in the surface depth layer lends support to the (490/555) pigment algorithm of Figure 4 as a suitably robust choice for estimating chlorophyll by remote sensing. The choice of $Rrs(490)/Rrs(555)$ seems more favourable as (a) the satellite signal at 490 nm is larger than that at 443 nm, particularly for pigment concentrations above 2 mg/m^3; (b) the ratio shows tight congruence with measured chlorophyll; and (c) 490 nm is less contaminated than 443 nm by yellow substance absorption, which decreases exponentially towards higher wavelengths[12].

Satellite-based comparisons

We have presented and discussed the bio-optical data measured *in situ* at several coastal stations on the cruise. In this section, we look at satellite and sea truth intercomparisons, namely between SeaWifs sensor estimates of radiance and chlorophyll with corresponding *in situ* data.

The processing of SeaWifs imageries was implemented with the SeaDas version 3.3 software running on a Sun Ultra 140 system (OS Solaris 7) and IDL 5.0. Atmospheric correction to retrieve the SeaWifs normalized leaving radiance was computed according to the standard Gordon and Wang algorithm[13]. A 1.1 km × 1.1 km area around the ship station coordinates was selected and the mean nor-
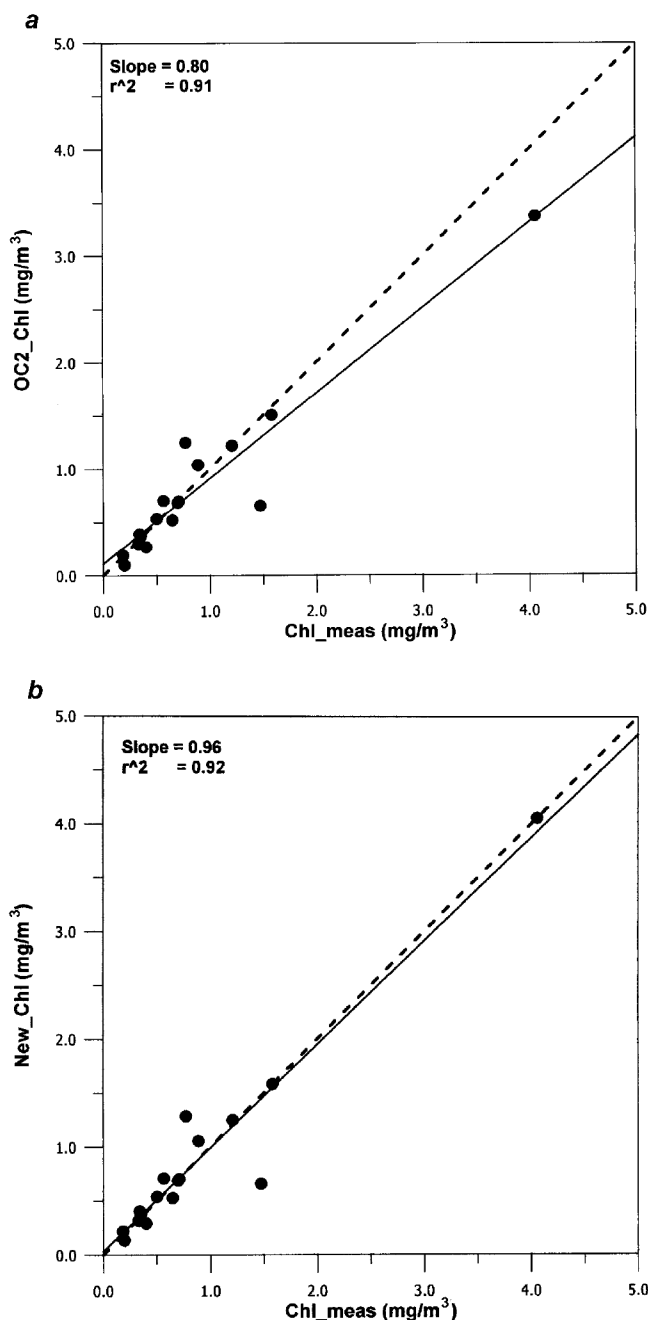

Figure 4. Linear regression as solid line for (a) OC2-V4 Chl a estimates against measured Chl a (●); and (b) modified algorithm Chl a estimate against measured Chl a concentrations at different cruise stations. Dashed line in (a) and (b) is the 1 : 1 line.
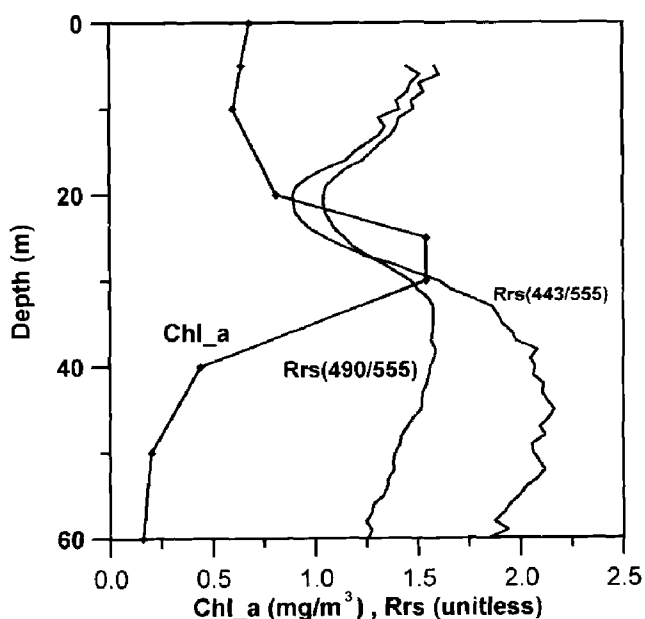
Figure 5. Vertical structure of the remotely sensed reflectance ratios (443/555) and (490/555) plotted for comparison with the measured chlorophyll profile at station 12. The same scale is used for both Chl a (mg/m^3) and the unitless Rrs ratio.

malized water-leaving radiances were computed over a 9 × 9 pixel array and used in the inter-comparisons.

SeaWifs and in situ radiances

A match-up to *in situ* data is considered satisfactory when a clear cloud-free patch exists around the ship coordinates, when the time difference between the radiometer casts and the satellite visit time over the ship is as small as possible, and not more than 2 h, and the satellite view angle is small, i.e. the ship location is well within the swath of SeaWifs pass.

We obtained acceptable SeaWifs match-ups at stations 6, 10, 20 and 22 only (see Table 1). An example of a processed SeaWifs chlorophyll image for the 20 November 1999 (station 6) is shown in Figure 6 where some clear patches were found. The cloud cover was more extensive for the other stations, 10 and 20, (22 and 26 November).

A spectral comparison between average SeaWifs-derived Lwn and the *in situ* estimates from the radiometer for the 4 match-up days is shown in Figure 7. Most of the points lie above the 1 : 1 line of perfect correspondence. We define the RMSD at any wavelength λ as:

$$\text{RMSD}\,(\lambda) = 100\sqrt{\left[N^{-1} \sum \frac{(Lwn^{\text{Sea}} - Lwn^{\text{Sat}})^2}{(Lwn^{\text{Sat}})} \right]},$$

where Lwn^{Sea} and Lwn^{Sat} are the average normalized water-leaving radiance estimates from SeaWifs and the Satlantic radiometer, respectively at the same station and

N is the number of matched stations, where the summation Σ is over N stations (here $N = 4$).

We find that RMSD values between SeaWifs relative to the *in situ* radiometric measurements are 43% at 412 nm, 97.6% at 443 nm, 63% at 490 nm, 74% at 510 nm and 79% at 555 nm. RMSD is largest for the 443 nm and least for 412 nm. There is a trend towards overestimation of water-leaving radiances by SeaWifs for the stations 6, 10, 20 and 22 considered in this inter-comparison.
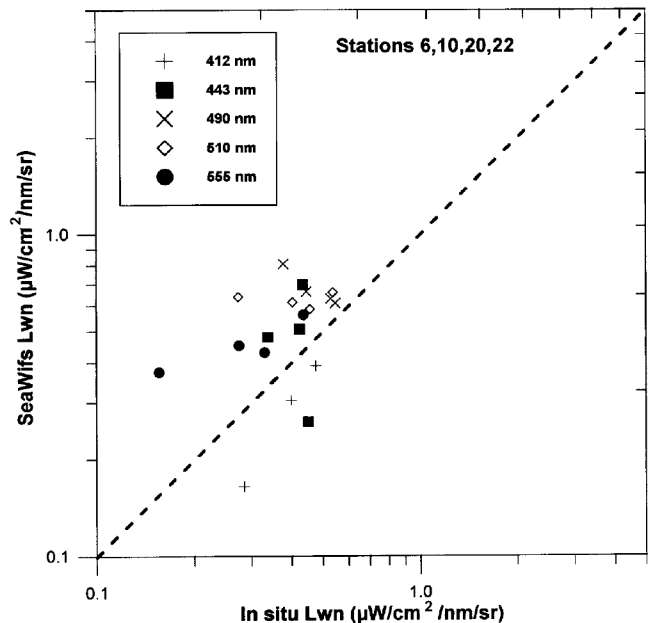

Figure 7. Graph showing overestimation of SeaWifs Lwn radiances with respect to *in situ* normalized water-leaving radiances for stations 6, 10, 20, and 22 where inter-comparisons were made.
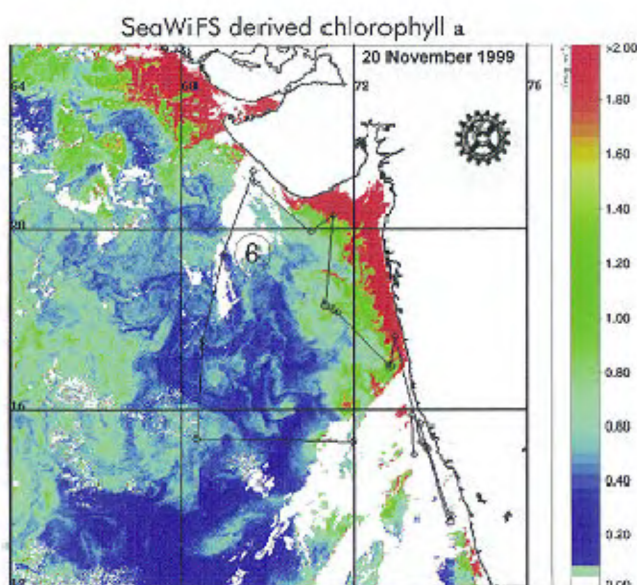

Figure 6. Processed SeaWifs image for 20 November 1999 with superimposed cruise track of *SK 149C*.
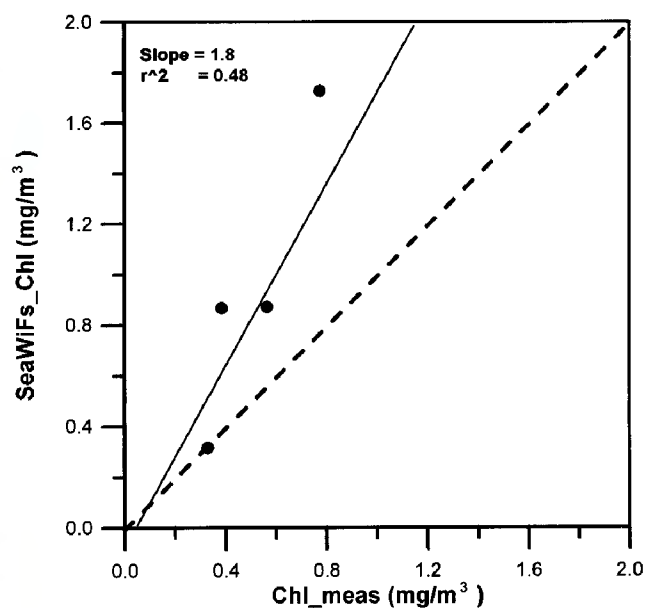

Figure 8. Graph showing overestimation of SeaWifs-derived chlorophyll using the OC2 algorithm in relation to measured *in situ* chlorophyll concentrations at the matched stations 6, 10, 20, and 22 where satellite validation was possible.

SeaWifs-derived chlorophyll and in situ chlorophyll

As a further inter-comparison, we have used the atmospherically corrected Lwn of Figure 7 in the standard OC2 algorithm to derive the SeaWifs-based estimate of chlorophyll. The comparison with *in situ* measured chlorophyll is shown in Figure 8. The SeaWifs sensors show gross overestimates of chlorophyll with an RMSD of ~ 93%, with contributing errors arising from the use of the OC2 algorithm and the overestimates in radiances discussed above.

Summary

The validation data reported in this paper have focused on bio-optical measurements made in the coastal waters of the Arabian Sea. The range of chlorophyll concentration was between 0.2 and 4 mg/m^3. Although the match-ups between *in situ* and satellite data were sparse, it is instructive to summarize the main results obtained, namely:

• Direct application of the standard OC2 algorithm in eq. (3) for the coastal waters of the Arabian Sea will more often than not underestimate chlorophyll concentration by as much as 26% as shown by the RMSD value. A modified algorithm fit shown in eq. (4) gives only marginal benefits in accuracy. When a comprehensive bio-optical data set from future cruises is assembled, a 'new algorithm' can evolve, to suit local Arabian Sea coastal waters. However, these new algorithms must be able to estimate not only chlorophyll, but also the other sea water constituents, namely suspended sediments, detritus, auxiliary pigments and yellow substance.

• With the available data set, SeaWifs shows a trend in overestimating the normalized water-leaving radiances and chlorophyll to those derived from *in situ* measurements. At the blue wavelength at 412 nm, the SeaWifs sensor underestimates frequently[14]. The errors in satellite estimates of radiance and chlorophyll must address at least two well-known problems, namely (a) an inaccurate SeaWifs Atmospheric Correction Algorithm[13] in coastal waters, and (b) probable enhanced particle backscattering that adds to the total water-leaving radiance (Lw).

Some authors have reported both overestimation[15] and underestimation[16] of SeaWifs water-leaving radiances

when compared to *in situ* radiometric measurements. This has been speculated as arising from difficulties in correcting atmospheric effects accurately in the coastal regions or increases in non-absorbing particle backscattering, typical of case 2 waters near the coast. In coastal regions, the water-leaving radiances in the IR bands are not negligible and aerosols are likely to be absorbing[16]. Further studies in this direction are necessary to resolve these problems of validating satellite sensors.

1. Smith, R. C., *Mar. Ecol. Prog. Ser.*, 1981, **5**, 359–361.
2. Gordon, H. R., *Appl. Opt.*, 1985, **24**, 4172–4182.
3. Gordon, H. R. and Ding, K., *Limnol. Oceanogr.*, 1992, **37**, 491–500.
4. Gordon, H. R. *et al.*, *J. Geophys. Res.*, 1988, 10909–10924.
5. O'Reilly, J. E. *et al.*, *J. Geophys. Res.*, 1998, **103**, 24,937–24,953.
6. Neckel, H. and Labs, D., *Solar Phys.*, 1984, **90**, 205–258.
7. Smith, R. C. and Baker, K. S., in *Ocean Optics VII* (ed. Slater, P. N.), SPIE, 1987, **637**, pp. 95–107.
8. Smith, R. C. and Baker, K. S., in *Ocean Optics VII* (ed. Blizard, M.), SPIE, 1984, **478**, 119–126,
9. Zaneveld, J. R. V., *App. Opt.*, 1982, **21**, 4146–4150.
10. Siegel, D. A. and Dickey, T. D., *Deep Sea Res.*, 1987, **34**, 547–563.
11. Smith, R. C. and Baker, K. S., *Limnol. Oceanogr.*, 1978, **232**, 260–267.
12. IOCCG Report No. 1, International Ocean Colour Coordinating Group (affiliated to Scientific Committee on Oceanic Research, SCOR), 1998.
13. Gordon, H. R. and Wang, M., *Appl. Opt.*, 1994, **33**, 443–452.
14. Zaneveld, J. R. V., Scott Pegau, W. and Barnard, A. H., in SIMBIOS Project Annual Report, NASA/TM-1999-209486, 1999, chapter 20, pp. 101–104.
15. Frouin, R., Cutchin, D. L. and Yves Deschamps, P., in SIMBIOS Project Annual Report, NASA/TM-1999-209486, 1999, chapter 11, pp. 65–68.
16. Greg Mitchell, R. and Flateau, P., in SIMBIOS Project Annual Report, NASA/TM-1999-209486, 1999, chapter 15, pp. 80–84.