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EVALUATING THE VALIDITY OF SeaWiFS CHLOROPHYLL ALGORITHM FOR COASTAL WATERS

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Abstract: The SeaWiFS ocean colour sensor on board the SeaStar (Orbview 2) satellite is able to derive the chlorophyll concentration in the surface sea water. The chlorophyll algorithm employed is based on the ratio of radiance or reflectance measured in the blue and green spectral bands. Regression between the band ratio and the in-situ measurements of chlorophyll values gives the coefficients for the retrieval equation. It is commonly known that the standard SeaWiFS chlorophyll algorithm (OC4) is generally applicable only in open ocean (case 1 waters). This algorithm is not expected to be valid in coastal waters (case 2 waters) containing other constituents such as sediments and dissolved organic matter. In this study, we simulate SeaWiFS reflectance spectra of coastal waters using an analytical model based on the quasi-single scattering approximation. The OC4 algorithm is then applied to the simulated spectra to derive chlorophyll concentration. The derived chlorophyll value are compared with the actual chlorophyll values used to generate the spectra. The results show that the OC4 algorithm is valid only for sea waters with low dissolved organic matter, but the accuracy deteriorates for typical coastal waters with high dissolved organic matter.

Keywords: Ocean colour; SeaWiFS sensor; Chlorophyll;

1. INTRODUCTION

The SeaWiFS sensor on board the SeaStar (Orbview 2) satellite (launched October 1997) provides ocean color data with about 1-km resolution. It has six bands in the visible region and two in the near-infrared region. Each band has a 20-nm bandwidth. Several algorithms exist for the retrieval of the chlorophyll concentration in sea water. A basic algorithm used to determine the chlorophyll concentration is based on the ratio of radiance or reflectance measured in the blue and green spectral bands (O'Reilly et al. 1998). A polynomial is usually used to represent the relation between the logarithm of the band ratios and the logarithm of chlorophyll concentration. The coefficients of the polynomial are found by regression between the band ratios and the sea-truth value of chlorophyll concentration measured from water samples taken at various places. This method based on band ratios works reasonably well in open ocean waters (case I waters), where chlorophyll and covarying substances such as detritus determine the optical properties (Morel 1996). Case II waters are characterized by high concentrations of chlorophyll, coloured dissolved organic matter (CDOM) or gelbstoff, and suspended matter. The scattering and absorption characteristics are now determined not only by chlorophyll, but also by CDOM and non-chlorophyllous suspended matters. Coastal sea waters are typically case II waters. The simple band ratio algorithms do not work well for this category of waters (Tassan 1994).

The aim of this study is to investigate how well the standard SeaWiFS OC4 chlorophyll algorithm (O'Reilly et al. 1998) is applicable to typical coastal sea waters. We simulate SeaWiFS reflectance spectra of coastal waters using an analytical model based on the quasi-single scattering approximation (Liew et al. 2001). The SeaWiFS OC4 algorithm is then applied to the simulated spectra to derive chlorophyll concentration. The derived chlorophyll values are compared with the actual chlorophyll values used to generate the spectra. The results show that the OC4 algorithm is valid only for sea waters with low dissolved organic matter, but the accuracy deteriorates for typical coastal waters with high dissolved organic matter.

2. MODELING THE REFLECTANCE OF SEA WATERS

The reflectance spectra of sea waters are simulated using the quasi-single-scattering approximation, ignoring any transpectral processes such as fluorescence and Raman scattering. The sea water reflectance can be shown to depend on the inherent optical properties according to (e.g. Sathyendranath and Platt 1997)

$$R(\lambda) = K \frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)} \tag{1}$$

where $b_b(\lambda)$ is the backscattering coefficient and $a(\lambda)$ is the absorption coefficient of the sea water. The parameter K is approximately wavelength independent.

The absorption coefficient $a(\lambda)$ is modeled by the sum of absorption coefficients due to water (w), phytoplankton (ϕ) and gelbstoff (g),

$$a(\lambda) = a_w(\lambda) + a_\phi(\lambda) + a_g(\lambda) \tag{2}$$

The backscattering coefficient is the sum of backscattering contributed by water and particulate matters (p),

$$b_b(\lambda) = b_{bw}(\lambda) + b_{bp}(\lambda) \tag{3}$$

The absorption and backscattering coefficients of water are taken from published tabulated values. The absorption coefficient of gelbstof is modeled by an exponential relation,

$$a_g(\lambda) = G\exp(-S(\lambda - 440)) \tag{4}$$

where G is the gelbstoff absorption at 440 nm, and the wavelength λ is measured in nm. The model for the phytoplankton absorption coefficient is adapted from an empirical model in Lee et al. (1998),

$$a_\phi(\lambda) = P_0 a_0(\lambda) + P_1 a_1(\lambda) \tag{5}$$

The parameter P_0 is the phytoplankton absorption coefficient at 440 nm, which varies with the chlorophyll concentration. The parameter P_1 is dependent on P_0. The particulate backscattering coefficient is modeled by an inverse power law,

$$b_{bp}(\lambda) = X\left(\frac{440}{\lambda}\right)^y \tag{6}$$

where X *is* the backscattering coefficients of particulates at 440 nm, and the exponent y gives an indication of the size of particles.

3. SIMULATING THE SeaWiFS REFLECTANCE SPECTRA FOR COASTAL WATERS

The parameters in the reflectance model that depend on the concentrations of the water constituents are: P_0, P_1, G, S, X, y. In a previous study, these parameters were derived from in-situ measurements of reflectance spectra by inverse modeling (Liew et al. 2001). By regressing the derived values of these parameters with the actually measured chlorophyll (Chl, in mg/m^3) and suspended sediments (TSS in g/m^3) for coastal waters around Singapore, the following relations were obtained:

$$X = 0.05192 + 0.0004889(\mathrm{TSS}) - 0.00000125\ (\mathrm{Chl})\ \ \mathrm{m}^{-1} \tag{7}$$

$$y = 0.9504 - 0.01135(\mathrm{TSS}) + 0.004764(\mathrm{Chl}) \tag{8}$$

$$G = 0.4801\ \mathrm{m}^{-1} \tag{9}$$

$$S = 0.02062\ \ \mathrm{nm}^{-1} \tag{10}$$

$$P_0 = 0.02062\ \ (\mathrm{Chl})^{1.291}\ \mathrm{m}^{-1} \tag{11}$$

$$P_1 = P_0\ \ln(P_0\ /10.55)\ \mathrm{m}^{-1} \tag{12}$$

The typical value of Chl is around 10 mg/m^3, and values of above 50 mg/m^3 has also been recorded. The mean value of TSS is about 20 g/m^3. The particulate backscattering coefficient at 440 nm (X) is found to increase weakly with TSS and practically not influenced by Chl. The exponent y in Eq. (6) decreases with increasing TSS, and slightly decreases with increasing Chl. The chlorophyll absorption coefficient at 440 nm (P_0) varies with Chl according to a power law (Eq. 11), while the absorption coefficient at 440 nm due to gelbstoff (G) is found to be relatively stable at 0.48 m^{-1} for the coastal Singapore waters.

Table 1: Spectral bands of the SeaWiFS sensor

Band Number	1	2	3	4	5	6	7	8
Band Centre (nm)	412	443	490	510	555	670	765	864
Bandwidth (nm)	20	20	20	20	20	20	40	40

SeaWiFS reflectance at all the eight bands (see Table 1) were computed for values of Chl ranging from 0.001 to over 50 mg/m^3 , TSS values from 0.001 to over 50 g/m^3 for two gelbstoff concentrations: G = 0.1 and 0.5 m^{-1}. In the simulation, a value of 0.33 was used for the constant K in Eq. (1).

4. SeaWiFS OC4 CHLOROPHYLL ALGORITHM

The SeaWiFS OC4 chlorophyll algorithm is a maximum band-ratio algorithm employing 4 spectral bands: Bands 2, 3, 4 and 5. Band 5 (555 nm) is taken as the reference wavelength band and three band ratios are computed for each measurement of the reflectance spectrum:

$$R_{ij} = r_i / r_j ; \quad i = 2,3,4; \ j = 5 \tag{13}$$

where R_{il} is the ratio of reflectances at band-*i* and band-*j*. The maximum of the three band ratios R_{max} = max{R_{ij}: *i*=2,3,4; *j*=5} is then taken as the parameter for calculating the chlorophyll concentration value according to the equation (O'Reilly et al. 1998):

$$\log_{10}(Chl - a_4) = a_0 + a_1 L + a_2 L^2 + a_3 L^3 ; \text{ where } L = \log_{10}(R_{\max}) \tag{14}$$

The coefficients a_i for the OC4 algorithm are

$$a_0 = 0.4708; \ a_1 = \text{-}3.8469; \ a_2 = 4.5338; \ a_3 = \text{-}2.4434; \ a_4 = \text{-}0.0414. \tag{15}$$

5. RESULTS

5.1 Simulated SeaWiFS Reflectance Spectra of Coastal Waters

The reflectance spectra of coastal waters computed using Eq. (1) for different combination of values of Chl, TSS and G are shown in Figure 1. Several observations can be made.

Effects of TSS: The effects of increasing TSS can be seen in Figures 1 (a), (c), and (e) for the case of *G*=0.1 m^{-1}, and Figures 1 (b), (d), and (f) for the case of *G*=0.5 m^{-1}. In general, for a given Chl and G, the effect of increasing TSS is to increase the reflectance value, without changing the shape of the spectrum. The backscattering coefficient of particulate matters $b_b(\lambda)$ is weakly dependent on wavelength, since the exponent *y* in Eq. 6 is close to 1. Hence, increasing TSS will not change the shape of the spectrum very much.

Effects of Chl: Generally, the spectra all have almost the same shape and reflectance values for Chl < 1 mg/m^3. Hence, no chlorophyll algorithm can be expected to yield accurate results for low Chl values in coastal waters. In the case of low gelbstoff concentration (*G*=0.1 m^{-1}), the peak location of the reflectance spectrum shifts from 490 nm to 510 nm and then to 555 nm as the chlorophyll concentration increases, due to chlorophyll absorption in the short wavelength region around 440 nm. However, the peak remains at 555 nm at high gelbstoff concentration (*G*=0.5 m^{-1} , typical for Singapore coastal waters). The reflectance values also generally decreases as chlorophyll concentration increases.

Effects of gelbstoff: Gelbstoff absorps strongly at short wavelengths. Thus, the gelbstoff absorption masks the effects of chlorophyll absorption at short wavelengths. At high *G*, the accuracy of chlorophyll algorithm is not expected to be good.

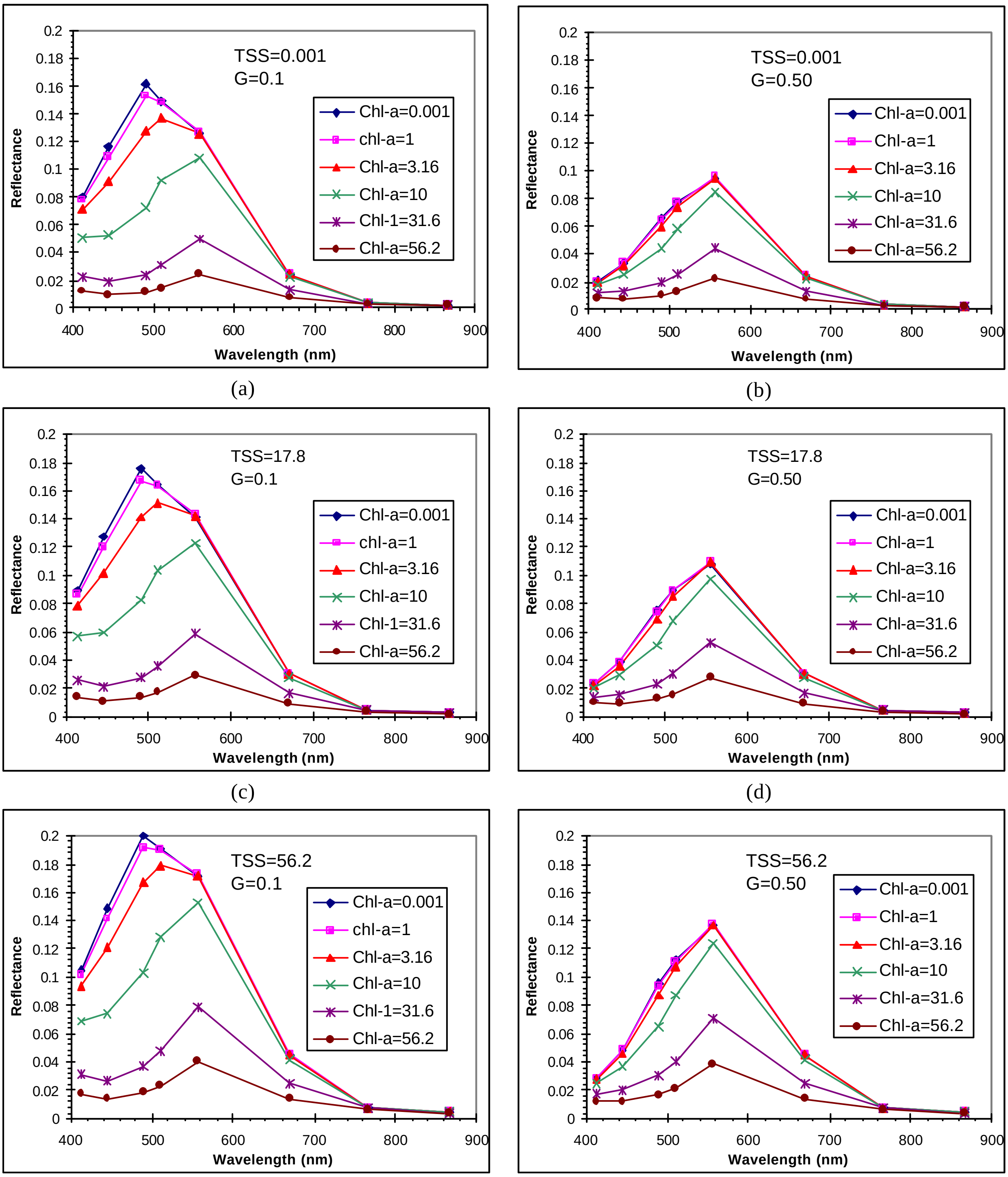
5.2 Accuracy of OC4 Chlorophyll Algorithm

Chlorophyll concentration was derived from each of the computed SeaWiFS reflectance spectra using the OC4 algorithm. In Figure 2, the Chl values derived from OC4 are plotted against the actual Chl values used in the computation of the spectra. In the case of low gelbstoff concentration (*G*=0.1 m^{-1}), the agreement between the derived Chl and the actual Chal values is generally good. However, at high gelbstoff concentration (*G*=0.5 m^{-1}) typical of Singapore coastal waters, the OC4 algorithm generally overestimates the chlorophyll concentration. The values of TSS generally does not affect the derived Chl values, except when the chlorophyll concentration exceeds about 30 mg/m^3. The values of OC4 derived chlorophyll concentration increases monotonically with the actual Chl values. Hence, even though the absolute value of the derived Chl is too high, the derived values do give correct indications of the relative Chl concentration.

6. CONCLUDING REMARKS

It has been recognised that the SeaWiFS standard chlorophyll algorithm is generally accurate for open ocean, but its validity is of suspect for coastal waters due to the compounding effects of suspended sediments and gelbstoff (coloured dissolved organic matter). In this study, we have evaluated the accuracy of the OC4 chlorophyll algorithm using simulated SeaWiFS reflectance spectra for coastal waters around Singapore. The separate effects on the reflectance spectra due to TSS, Chl and gelbstoff are examined. The results confirm that OC4 generally oversestimates the chlorophyll concentration of coastal waters with high gelbstoff concentration..

The simulated SeaWiFS reflectance spectra were computed using Eq. (1). This equation is sufficiently general to be applicable for both case 1 and case 2 waters. The inputs to Eq. (1) are the optical properties (especially the absorption and scattering coefficients) of the separate constituents of sea water. The relations between the optical properties and the concentrations of sea water constituents need to be know before the reflectance spectra can be computed. In this study, the relations in Eq. (7) to Eq. (12) have been derived by regression of the optical parameters (derived from measured reflectance using an inverse modeling method) and the measured TSS and Chl values, acquired during sea-truth campaigns in coastal waters around Singapore. This set of relations may not be applicable for coastal waters in other locations.

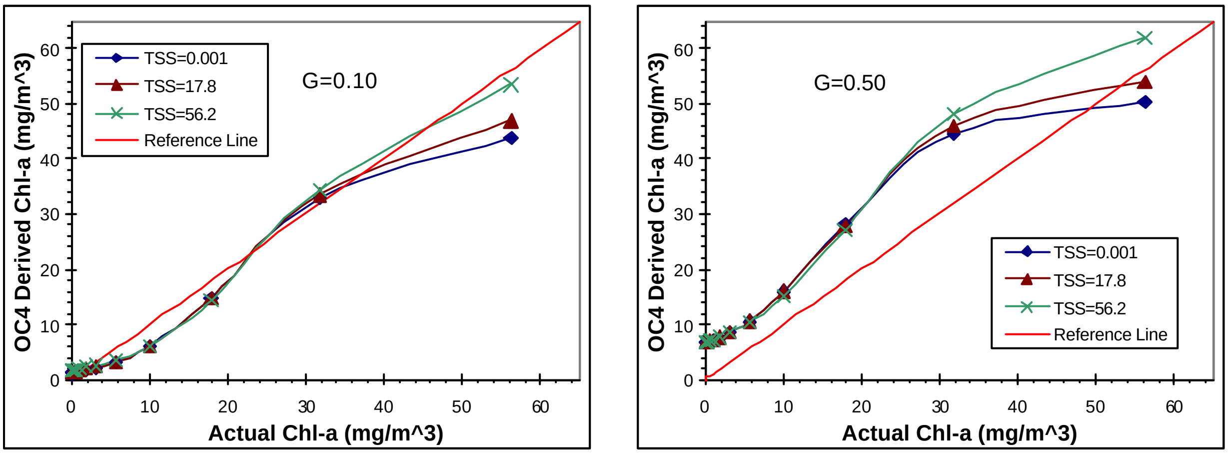


(a) (b)

(c) (d)

(e) (f)

Figure 1: Simulated SeaWiFS reflectance of coastal waters for various Chl concentration and (a) low TSS, low G; (b) low TSS, high G; (c) typical TSS, low G; (d) typical TSS, high G; (e) high TSS, low G; (f) high TSS, high G.



(a) (b)

Figure 2: Accuracy of the SeaWiFS OC4 chlorophyll algorithm for coastal waters: (a) low gelbstoff concentration (G=0.1 m^{-1}); (b) high gelbstoff concentration (G=0.5 m^{-1}).

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