

Development of Suspended Particulate Matter Algorithms for Ocean Color Remote Sensing

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Abstract : We developed a CASE-II water model that will enable the simulation of remote sensing reflectance(R_{rs}) at the coastal waters for the retrieval of suspended sediments (SS) concentrations from satellite imagery. The model has six components which are: water, chlorophyll, dissolved organic matter (DOM), non-chlorophyllous particles (NC), heterotrophic microorganisms and an unknown component, possibly represented by bubbles or other particulates unrelated to the five first components. We measured R_{rs} , concentration of SS and chlorophyll, and absorption of DOM during our field campaigns in Korea. In addition, we generated R_{rs} from different concentrations of SS and chlorophyll, and various absorptions of DOM by random number functions to create a large database to test the model. We assimilated both the computer generated parameters as well as the *in-situ* measurements in order to reconstruct the reflectance spectra. We validated the model by comparing model-reconstructed spectra with observed spectra. The estimated R_{rs} spectra were used to (1) evaluate the performance of four wavelengths and wavelengths ratios for accurate retrieval of SS. 2) identify the optimum band for SS retrieval, and 3) assess the influence of the SS on the chlorophyll algorithm. The results indicate that single bands at longer wavelengths in visible yield better results than commonly used channel ratios. The wavelength of 625nm is suggested as a new and optimal wavelength for SS retrieval. Because this wavelength is not available from SeaWiFS, 555nm is offered as an alternative. The presence of SS in coastal areas can lead to overestimation chlorophyll concentrations greater than 20 - 500%.

Key Words : CASE-II Water, Remote Sensing Reflectance Model, SS Algorithms.

1. Introduction

The first quantitative estimation of SS from a space borne sensor came from the Coastal Zone Color Scanner (CZCS). The algorithms involved in these determinations used the ratio of spectral radiances at 440 nm and 550nm (Clark *et al.*, 1981).

These are the same bands used for chlorophyll algorithms. While chlorophyll algorithms have progressed to the point that they can be used operationally in CASE-I waters, those for chlorophyll and SS in CASE-II waters (Gordon and Morel, 1983) are still at the level of basic research. However, the accurate estimation and

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understanding of the influence of SS on chlorophyll algorithms is essential for developing CASE-II reflectance algorithms. Unfortunately, the optical properties of SS in seawater are not well known. Bukata *et al.* (1981) estimated specific absorption coefficient (a^*) and specific backscattering coefficient (b_b^*) of SS using surface reflectance measurements in Ontario Lake, Canada. Withlock *et al.* (1981) also measured bb of turbid water with a volume scattering function. Ahn (1990) measured the absorption and backscattering coefficients of mineral particles (soil) suspended in seawater in-vitro. In 1997, Ahn *et al.* (1997) developed a methodology for quantifying the SS contribution to the total reflectance. Measurements by Ahn and Bukata's results showed some disagreement.

We know that the presence of SS introduces large errors in the estimation of chlorophyll in ocean color satellite imagery, and that there is a need to quantify the SS error contribution to the signal and to identify the optimum the bands for estimating SS. The need to understand and improve our knowledge of the influence of SS on chlorophyll algorithms in ocean color technique largely motivated this study. In this paper, we report our efforts to model CASE-II water reflectance, and to estimate the influence of SS on chlorophyll algorithm. We compare the model estimations to *in-situ* measurements.

2. Method

1) Field Measurements

Remote sensing reflectance was measured from 400nm to 700nm at 2nm intervals with a field dual direction spectroradiometer (ASD Inc.). Total

suspended solid particulates, chlorophyll concentration, and DOM absorption were measured *in-situ*. DOM was measured at the same wavelengths as those of the remote sensing reflectance. The measurements were obtained in CASE-II turbid water and in clear water, around the Korean peninsular from 1998 to 2001. The *in-situ* values were used to validate the modeled reflectance, and to develop SS algorithms for this ocean color sensor.

2) Remote Sensing Reflectance Model for CASE-II Waters

A remote sensing reflectance model for extracting the SS contribution to the total signal was developed using six water components: water, phytoplankton, DOM, suspended mineral particles, heterotrophic organism and unknown components. This model follows a similar conceptual basis as the irradiance reflectance model previously developed by Ahn (1990 and 1999). From satellite signals, we extract water leaving radiance (L_w) or normalized water-leaving radiance (L_{wN}).

To simplify the R_{rs} model, we assume clear skies, the sun position always at noon, a satellite-sensor viewing angle within 20 degree from nadir, and no sun glint in the sensor direction. Irradiance reflectance (R) computed in previous research by Prieur and Morel(1975) was found to be related to inherent optical properties of water such as total beam absorption (Σa) and total backscattering coefficient(Σb_b).

$$R(0^-) = f \frac{\Sigma b_{bi}}{\Sigma a_i + \Sigma b_{bi}} \quad (1)$$

where f varies weakly as a function of the volume scattering function of particles in seawater and of the radiance distribution within the submarine

light field. 0^- means just beneath of surface. R is the irradiance ratio or irradiance reflectance defined again by

$$R(0^-) = \frac{E_u(0^-)}{E_d(0^-)} = \frac{Q_u L_u(0^-, \theta, \varphi)}{(1-\rho) E_d(0^+)} \quad (2)$$

where, $L_u(0^-, \theta, \varphi)$ is the upwelling radiance in the direction of zenith(θ) and azimuth(φ) angles just beneath the surface. E_u and E_d are the upward and downward irradiance respectively. E_u can be changed to L_u by multiplication of π and L_u if the ocean is a diffuse Lambertian reflector (isotropic $L_u(\theta, \varphi)$ in all directions). In practice, the ocean is not a homogeneous reflector, Q_u is not a constant but a function of depth and direction (θ, φ). Q_u is not especially sensitive to wavelength and illumination. According to Austin (1974 and 1980), if L_u is the radiance in the nadir direction, π must be replaced by a factor close to 5. As we assume above, if the optical sensor position is fixed, i.e. sun position and sensor viewing angle are within the 20 degrees from nadir, L_u is then no longer a function of zenith and azimuth angles.

To convert $E_d(0^-)$ to $E_d(0^+)$, the relationship of $E_d(0^-) = (1-\rho) E_d(0^+)$ was used, where ρ is averaged Fresnel reflectance (air to water) of the downwelling irradiance for clear skies and for a given sun elevation. The values of ρ can vary with sky conditions (cloud distribution), sun elevation, and sea surface state (wind speed). According to Morel and Gentili (1996), ρ values occur within the range of 4 – 5%. Our *in-situ* measurements indicated that ρ varies from 5% (clear sky) to 15%(cloudy sky). In this study, we adopted a ρ value of 5% for clear sky.

Even though R_{rs} , strictly speaking, cannot be called “reflectance” because it has units of sr^{-1} , to link the irradiance reflectance to the remote sensing reflectance, the following relation was

used,

$$R_{rs} = \frac{L_w}{E_d(0^+)} = \frac{L_{wN}}{F_0} \quad (3)$$

where L_w is the water leaving radiance ($=L_u(0^+)$), and L_{wN} is the normalized water leaving radiance. F_0 is the extraterrestrial solar irradiance. Using the radiance transmitted through the water-air interface ((Fresnel n^2 Law, and $n = 1.34$ (Gordon and Morel, 1983)), L_w can be expressed as,

$$L_w = 0.545 L_u(0^-) \text{ (or } L_u(0^-) = 1.83 L_w) \quad (4)$$

Combining Eq. (1), (2), (3) and (4), we obtain,

$$R_{rs} = \frac{1}{1.93} \frac{f}{Q_u} \frac{\sum b_{bi}}{\sum a_i + \sum b_{bi}} \quad (5)$$

where f/Q_u is a non-constant optical environmental factor. f is directly proportional to Q_u (Zaneveld, 1995). These two quantities follow similar trends with changing sun-angle. The range of variability of f/Q_u is less than that of the two individual parameters f and Q_u (Morel and Gentili, 1996). According to the results of their computer simulations, f/Q_u ranges from 0.075 to 0.095 for the various optical conditions (see, Fig. 6. in Morel and Gentili, 1996). In considering the sensor-viewing angle (10 – 20 degree from nadir) and the case of turbid water, a value of 0.085 was adopted in the following equation;

$$R_{rs} = 0.044 \frac{\sum b_{bi}}{\sum a_i + \sum b_{bi}} \quad (6)$$

The constant 0.044 in Eq. (6), which appears in previous work by Ahn (2000) as 0.047, is replaced in this study. To validate above model, R_{rs} spectrum values were generated from 400nm to 700nm at 2nm intervals using only 3 components values; phytoplankton(chlorophyll) concentration, NC, and DOM values. To generate R_{rs} spectra from the model, total absorption and backscattering

coefficients were separated into the six in-water components as follows.

- ① water (w)
- ② phytoplankton (ph)
- ③ non chlorophyllous particle(NC)
- ④ dissolved organic matter (DOM)
- ⑤ heterotrophic plankton (he)
- ⑥ unknown components (?)

The unknown components can be the wind-generated micro-bubbles generated in surface water (Stramski, 1994; Ahn, 2000) or sub-micron particles unrelated to the other components in the model. The backscattering coefficient of the unknown components was estimated using Ahn's (2000) method. Non-chlorophyllous particle are mostly mineral in nature, but their optical properties change with the seawater type. The optical properties of NC in seawater are unknown. To fill this absence in our data, we used the optical properties of loess from previous work by (Ahn, 1990).

The total backscattering term, $\sum b_{br}$, is the sum of b_{bw} , b_{bph} , b_{bNC} , and b_{bhe} , and $b_{b?}$. We did not include the backscattering value by DOM and absorption by the unknown components because they are considered negligible for purposes of these computations. The absorption and backscattering coefficients for each components are separated to their specific absorption(a^*) and backscattering coefficients(b_b^*), and concentration($\langle i \rangle$) values ($a_i = a_i^* \times \langle i \rangle$ and $b_{bi} = b_b^* \times \langle i \rangle$). (Ahn, 1999)

The model developed and expressed in Eq. (6) is applicable to both CASE-I and CASE-II waters. To test the performance of the model, we assimilated concentration ranges of each of the individual components. Concentrations of chlorophyll and NC, and $a_{DOM}(400nm)$ values were obtained from random number generation. These ranges were:

- 1) For the CASE-II water model, 1 to 100 g/m³ for NC, 0.1 to 2 mg/m³ for chlorophyll, and 0.1 to 1.0m⁻¹ for DOM absorption coefficient (400nm)
- 2) For the CASE-I water model, 0.1 to 1.0 g/m³ of NC values, 1 to 100 mg/m³ of chlorophyll, and DOM absorption coefficients 0.02 to 0.2m⁻¹ at 400 nm.

The R_{rs} spectra resulting from these simulations were used to examine the following questions:

- A. What is the optimum band or wavelength to extract the NC spectral contribution from R_{rs} ?
- B. How accurate is the existing two-band ratio algorithm in quantifying the SS spectral contribution?
- C. Can we derive an algorithm that properly quantifies SS from *in-situ* measurements?

Eq. (6) (R_{rs}) was transformed to "normalized water leaving radiance" (L_{wN}) to provide this algorithm in terms that SeaWiFS users can relate.

$$L_{wN} = F_o \times R_{rs} \quad (7)$$

3. Results and Discussion

1) Validation of CASE-II R_{rs} Model

We compared two sets of reflectance spectra: An *in-situ* spectra obtained during our field campaigns and a modeled spectra obtained when *in-situ* measurements were assimilated into our CASE II model. Fig. 1 depicts both sets of spectra. In the upper panel of this figure, are the comparisons of the spectra for coastal semi-clear waters. The lower panel shows comparisons of the two spectra for coastal eutrophic waters. Our results indicate that the R_{rs} spectra changed with the specific optical properties of in-water components and their concentrations. The shape

of the spectra was also different for clear coastal waters than for turbid waters.

The results of the simulations show that the developed R_{rs} model compare very well with *in-situ* water remote reflectance spectra. In certain situations, the model couldn't reproduce the *in-*

situ values as well as it did in others. We believe the disagreement occur as a result of abnormal sky light dispersion caused by dense clouds or aerosol distribution, or by sea surface roughness. The field spectroradiometer measures both the above-water remote sensing reflectance and the

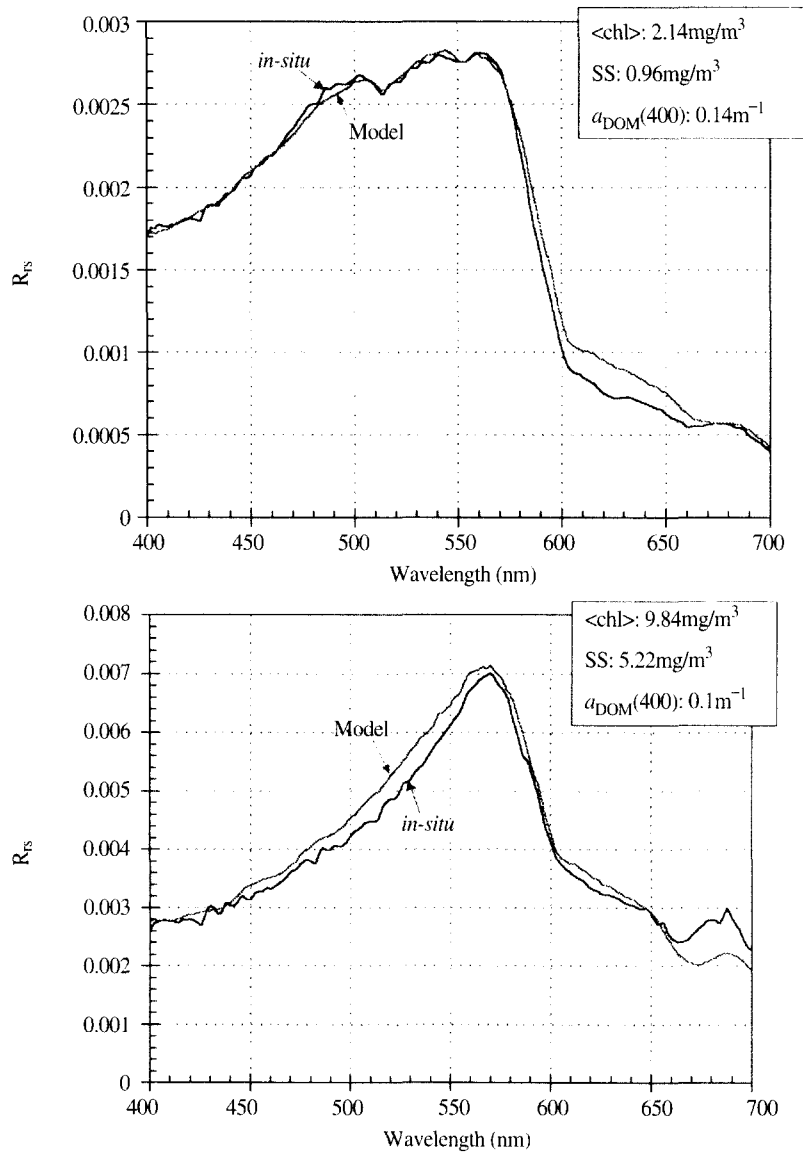


Fig. 1. Comparison of modeled and observed (*in-situ*) remote sensing reflectance spectra from two optically different waters. The modeled spectra resulted from the assimilation of the *in-situ* chlorophyll, SS concentrations, and DOM absorption at 400 nm into Eq. (6).

surface reflection from skylight. Surface reflection introduced the largest error in the R_{rs} measurements.

2) Determination of Optimal band for SS Algorithm

To assess the optimal band for quantification of SS, we evaluated four bands at 444, 555, 625 and 670 nm. The algorithms for SS are obtained by the empirical method depicted in Eq. (8). The expressions are the same as those of chlorophyll algorithms, i.e.,

$$\langle SS \rangle = A (r_{ij})^B \quad (8)$$

where A and B are coefficients obtained from statistical correlations. r_{ij} is the reflectance or radiance ratio, which can be the radiance normalized to the extraterrestrial solar irradiance or reflectance. Table 1 shows the results of SS algorithms obtained according to selected bands from the model generated R_{rs} spectrum using log transformed linear regressions. The results are very interesting. The two-band algorithm had the worst performance of all the algorithms tested, and the single-band algorithm at 670nm the best. The correlation coefficient, R^2 increased with increase in wavelength. This can be attributed to the stronger influence of the phytoplankton pigment and DOM in the green band (444nm) than in the red band (670nm). In practice, 670nm (including NIR) band is not useful for SS analysis

in the seawater because of the strong light absorption by water itself, which produces weak signal and little information of other layers besides the skin surface. Therefore, the optimal algorithm is that which allows for deeper penetration in the water column and less influence of the phytoplankton pigment and DOM absorption. Ideally, these algorithms can be generated at 625nm or 555nm.

The results of the study indicate that the optimum band for determination of SS is 625nm. Unfortunately 625nm is not available from SeaWiFS. We propose here that his new 625nm band be included in future ocean color sensors to enable the characterization of SS from space. The remote sensing reflectance model made possible the evaluation of each of these bands, and the identification of the optimum band for SS measurements. It also allowed us to compare the performance of the two-band ratio algorithm vs. that of individual bands. One-band algorithms are mathematically stronger, but they can be also more susceptible to atmospheric fluctuations than two-band algorithms.

3) SS Algorithms and *in-situ* Measurement

Algorithms for SS are empirical and calibrated via correlation with *in-situ* data. The previous CZCS SS algorithms were computed from two spectral radiance ratios of the blue (440nm) to the green (550nm) band or the green to the red

Table 1. Results of evaluation of individual bands and their capability to quantify SS. The test bands appear in the first column, the computed correlation coefficients appear in the second column. Origin and description of the bands tested are shown in the last column.

Bands [r_{ij}]	Correlation	R^2	Remarks for SS algorithm
$R_{rs}444/R_{rs}555$		0.85	Previously used bands
$R_{rs}555$		0.90	Suggested single band
$R_{rs}625$		0.98	New suggested band
$R_{rs}670$		0.99	SeaWiFS band

(670nm) band (Clark *et al.* 1980). Fig. 2 shows the relationship between the measured *in-situ* SS concentrations and R_{rs} (555nm). The obtained SS algorithm is;

$$\langle SS \rangle [g/m^3] = 463 R_{rs} (555)^{0.95} \quad (9)$$

if we replace R_{rs} with normalized water leaving

radiance(L_{wN} : mW/cm²/μm/sr), we obtain;

$$\langle SS \rangle [g/m^3] = 3.18 L_{wN} (555)^{0.95} \quad (10)$$

Note that the suspended solid in the model, NC, is not same as the total SS, NC is mineral particles, which constitute a portion of the total SS.

Fig. 3 shows a comparison of simulated NC and

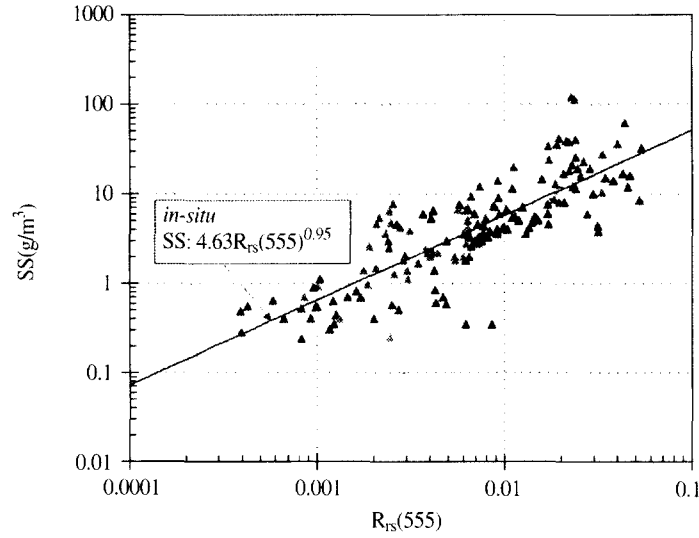


Fig. 2. Total suspended solid concentration, SS[g/m³], plotted vs. remote sensing reflectance at 550nm.

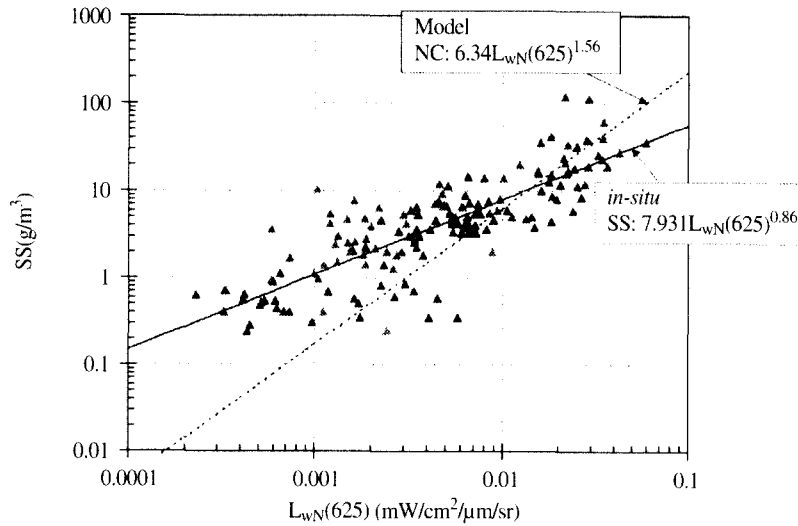


Fig. 3. Total suspended solid concentration, SS[g/m³], plotted vs. normalized water leaving radiance at 625nm, and model's NC regression line compared with *in-situ* SS algorithm.

measured SS [g/m^3] concentrations vs. L_{wN} at 625nm. In clear water where SS values are low, and the NC values are significantly smaller than SS, the effect on the signal is small. Conversely, in turbid waters, the SS values are high, and the NC values approach the total concentration of SS, the effect is rather large. In some cases the NC concentrations were observed to be higher than those of the SS. This cannot occur in nature and is considered to be an error in the model, which we intend to correct in the future. Contrary to our expectation, there was very little difference among the correlation coefficients calculated for the different bands selected (Table 2). In addition, the correlation values were low (< 0.78). Although many factors could be responsible for this, we suspect that the low correlations resulted from errors in our *in-situ* measurement technique. We utilized an above-water instrument rather than an underwater sensor, which would have been more accurate. Even though surface reflections are customarily removed from the measurements by computations of the sky radiance and Fresnel coefficients, upwelling radiance are easily contaminated by irregular water surface reflection.

The SS algorithm (Eq. 9) is applied to SeaWiFS ocean color satellite data to examine if the extractions of SS values are reasonable or not. Fig. 4 show the result of SS distribution image

obtained from SeaWiFS over Korea and adjacent areas on 14 April 1999. In the coastal areas of the Yellow Sea and South Sea, SS values range 5 – 100 g/m^3 . In the Yellow Sea trough deeper than 40 m, SS is reduced to 1 – 4 g/m^3 . High turbidity is found around Jin-do and Wan-do Island in the southwestern coastal area of the Korean peninsular. However, the center of Yellow Sea is very clear and SS concentrations are frequently found to be less than 0.5 g/m^3 . The SS distributions from the model agree very well with ship measurements (Ahn, unpublished data).

4) Influence of SS on <chl> Algorithm

Although we know that SS influences the chlorophyll concentration retrievals from satellites, we do not know how much. To estimate this question, first, CASE-I water algorithm was made from the model generated two bands Rrs ratio values (444nm/555nm) using CASE-I water model condition(right side line in Fig. 5), and also two bands R_{rs} ratio (444nm/555nm) values were generated from CASE-II water model (scattered points in Fig. 5). The CASE-I water algorithm overestimates the chlorophyll concentrations by a factor of one order difference if we apply CASE-II Rrs ratio values to CASE-I regression line. Fig. 5 shows that the presence of SS at the same time as chlorophyll pigment produces overestimation of the chlorophyll concentration in satellite retrievals.

Table 2. Suspended sediments algorithms, using 1 band, obtained at SeaWiFS bands (except 625nm) from *in-situ* measurement. Note that L_{wN} unit is [$\text{mW/cm}^2/\mu\text{m/sr}$]

Bands [r_{ij}]	Correlation	A	B	R^2
R555		463.0	0.95	0.75
L_{wN555}		3.18	0.95	0.75
R625		647.8	0.86	0.78
L_{wN625}		7.93	0.86	0.78
R670		209.7	0.69	0.74
L_{wN670}		6.38	0.69	0.74

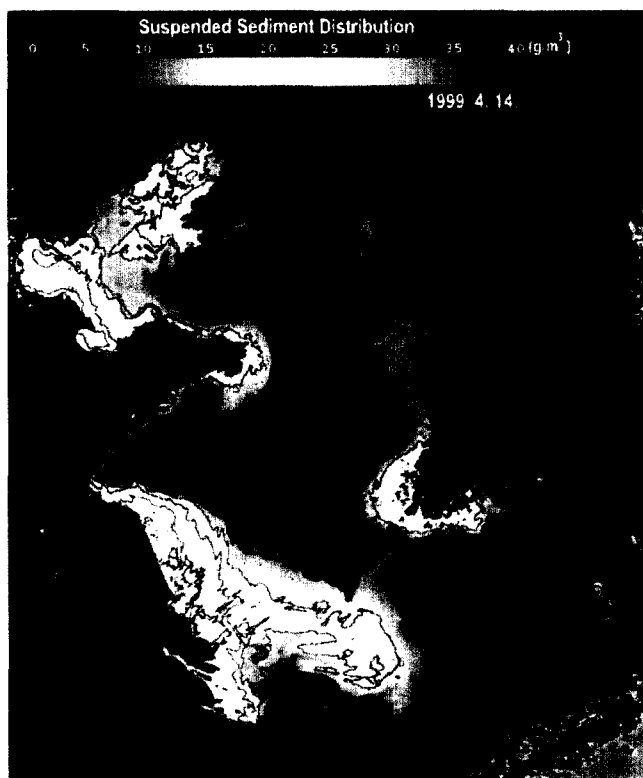


Fig. 4. Suspended solid particles distribution in 14 April, 1999 as observed by SeaWiFS ocean color satellite.
The image was processed with the SS algorithm (Eq. 9).

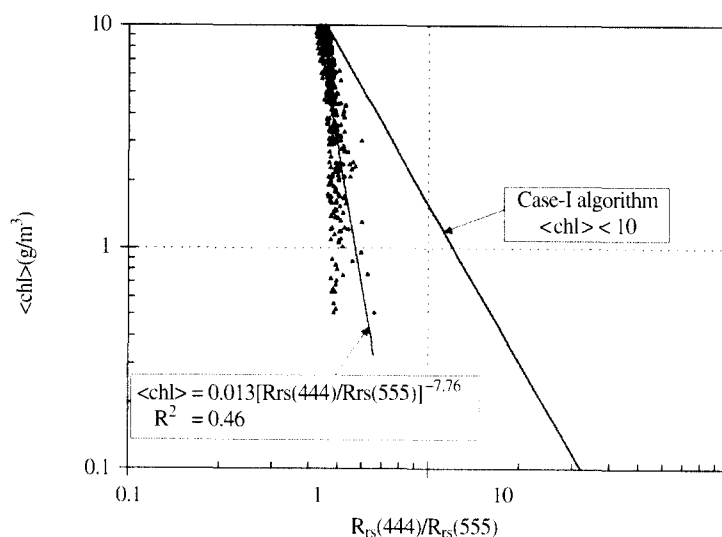


Fig. 5. Estimated reflectance ratios computed by the CASE-I water and CASE-II water models vs. chlorophyll concentrations. The right line shows the chlorophyll algorithm line obtained using CASE-I water model, and the left line that computed by the CASE-II water algorithm. Overestimation by the CASE-I algorithm is readily apparent.

The overestimation can be of 20-100% in eutrophic waters, and 2-5 time or more in oligotrophic waters where chlorophyll concentration is lower than 0.3mg/m^3 (and high SS content). The SS influence is reduced with increase of chlorophyll values.

4. Conclusions

We developed a CASE-II water remote sensing reflectance model for SS that closely reproduces the R_{rs} spectrum obtained from *in-situ* measurements. Although the model is very accurate, it is also influenced by many environmental and optical factors inherent to both *in-situ* and remotely acquired measurements. Among these sources of variability are: 1) the composition of the SS, which is different for different regions, and 2) the amount of SS particles present at a specific time and place, which is both a function of the local current regime and sediment type. In this study we did not address the spectral contribution of the bottom sediment and biological detritus. Other sources of variability include differences in sky light, viewing angle, and solar altitude.

Although we feel confident that this model will produce useful products in other areas, we believe that adding biological detritus and sediment components will greatly improve the accuracy of our CASE-II water model. To extend its capability to operate accurately in other geographical areas, we need a larger *in-situ* database from other coasts.

Besides providing accurate assessments of the SS spectral contribution to the total reflectance obtained by satellites, the R_{rs} model also provided us with the capability to determine the best

wavelengths for assessing SS. Our results indicate that the best wavelength for SS determination is 625nm. Computations utilizing this wavelength produced more accurate and precise results than computations based on the customarily used the two-bands ratio algorithm. Since this band is not currently available in SeaWiFS, we suggest using the next best band, which is 555nm for assessment of SS. We propose also new 625nm band algorithms for SS analysis in future ocean color sensors.

$$\langle \text{SS} \rangle [\text{g/m}^3] = 647.8 R_{rs} (625)^{0.86}$$

$$\langle \text{SS} \rangle [\text{g/m}^3] = 7.93 L_{wN} (625)^{0.86}$$

The above algorithms can be adapted to a particular region by assimilating *in-situ* data obtained in that region.

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