Modeling the optical properties of phytoplankton and their influence on chlorophyll estimation from remote sensing algorithms

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Abstract: The absorption coefficient and backscattering properties of phytoplankton were calculated from the Mie theory. Given a simple case that phytoplankton and mineral particles are the only constitutions in seawater, the reflectance $b_b(\lambda)/[a(\lambda)+b_b(\lambda)]$ was analyzed. Then the chlorophyll concentrations were estimated from remote sensing OC2 algorithm. The results show that reflectance in short wavelength region is more sensitive to the *Chl* variation; High mineral concentrations in seawater have significant influence on the reflectance spectrum; the existence of high mineral concentration may result in the mistake in chlorophyll estimation from OC2 algorithm.

Key words: ocean optics; Mie theory; phytoplankton; absorption property; backscattering property

1. Introduction

Ocean color can be considered a spectra expression of the light near or leaving the surface of the sea, and can be considered as the reflectance (Bernard, 2001)

$$R(\lambda)=\frac{E_u(\lambda)}{E_d(\lambda)}\approx 0.33\frac{b_b(\lambda)}{a(\lambda)+b_b(\lambda)} \quad (1)$$

Seawater and its constituents thus affect ocean color through the absorption and backscattering coefficient, as given by the above expression. Among the various dissolved and suspended particulate substances governing the optical properties of the natural water, phytoplankton plays a predominant role in the South China Sea. If the absorption and scattering properties of phytoplankton governing the regional optical properties can be understood deeply, ocean color measurement can therefore provide a powerful tool for ecological studies in South China Sea.

In this study the absorption and backscattering properties of phytoplankton are calculated by Mie theory modeling and we also analysis how variations in the size distribution and complex refractive index of phytoplankton affect the optical properties.

2 Theoretical backgrounds

2.1 modeling absorption and backscattering efficiency factors

For homogeneous spherical particles, absorption and backscattering efficiency factors $Q_a(\lambda)$ and $Q_{bb}(\lambda)$ can be precisely determined by the Mie theory. These factors are expressed as functions of Mie coefficients $a_N(m,x)$ and $b_N(m,x)$, where $m=n-in'$ is the complex refractive index of the particles relative to the surrounding media, $x=\pi D/\lambda$ is the relative size of particle (λ is the wavelength in the surrounding medium).

the absorption and backscattering efficiency factors are expressed as:

$$Q_c=\frac{2}{x^2}\sum_{N=1}^{\infty}(2N+1)\mathrm{Re}(a_N+b_N) \quad (5)$$

$$Q_b=\frac{2}{x^2}\sum_{N=1}^{\infty}(2N+1)(|a_N|^2+|b_N|^2) \quad (6)$$

$$Q_a=Q_c-Q_b \quad (7)$$

$$Q_{bb}=\frac{1}{x^2}[\sum_{n=1}^{\infty}(-1)^n(2n+1)(a_n-b_n)]^2 \quad (8)$$

2.2 modeling the absorption and backscattering coefficients

For the actual polydispersed population, the relation is then transformed into:

$$a=\frac{\pi}{4}\int_0^{\infty}Q_a(d)d^2F(d)d(d) \quad (10)$$

and if the specific absorption coefficient, $a^*(=a/C)$ is considered, the equation (10) need to transformed into

$$a^*=\frac{\pi}{4C}\int_0^{\infty}Q_a(d)d^2F(d)d(d)$$

$$=\frac{3}{2c_i}\frac{\int_0^{\infty}Q_a(d)F(d)d^2d(d)}{\int_0^{\infty}F(d)d^3d(d)} \quad (11)$$

Where c_i is the mean intracellular concentration of pigment, and $F(d)d(d)$ is the number of particles per unit

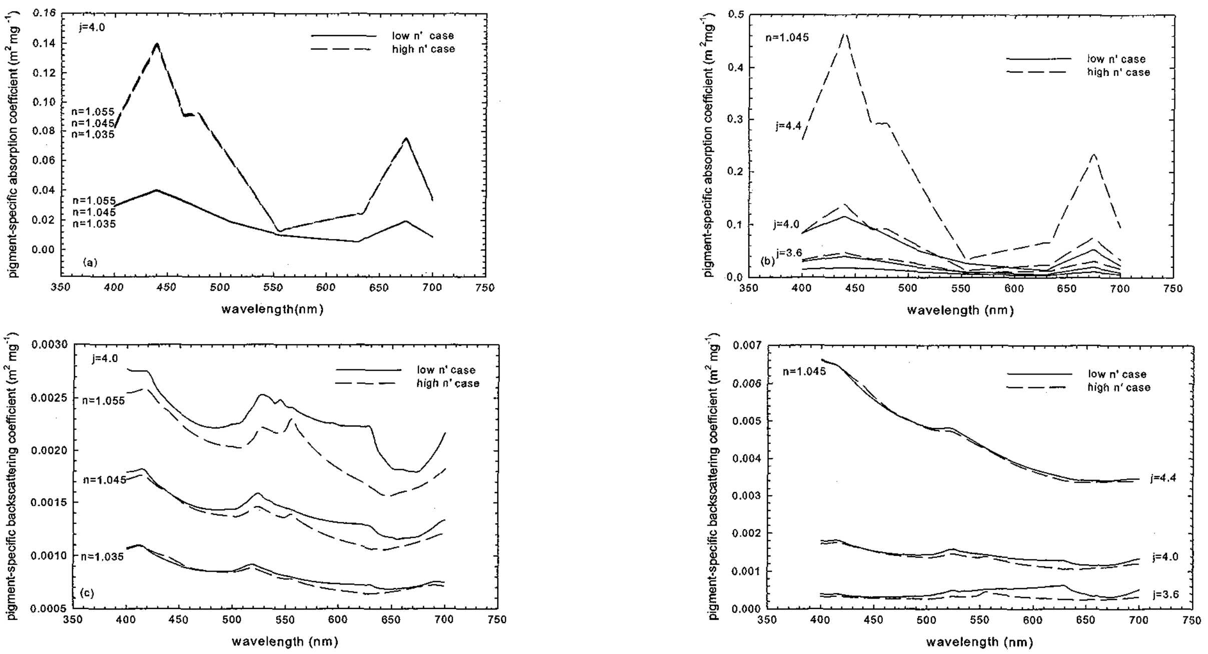

Fig. 1 (a) Effects of the real part of the refractive index, n, on the pigment-specific absorption coefficient of phytoplankton, a^*, for the slope of particle size distribution, $j = 4.0$. These effects are shown for the low n' case (solid curves) and the high n' case (dashed curves); (b)Effects of the slope of particle size distribution, j, on pigment-specific absorption coefficient of phytoplankton, a^*, for the given real part of the refractive index, $n = 1.045$. These effects are shown for the low n' case (solid curves) and the high n' case (dashed curves); (c) and (d) as (a) and (b), but for pigment-specific backscattering coefficient of phytoplankton.

volume in the size range $d \pm 1/2\, d(d)$. The relations similar to Equation (9), (10) and (11) link b_b and b_b^* to $Q_{bb}(\lambda)$.

3 Application to phytoplanktonic cells

We have chosen two different phytoplankton *Dunaliella bioculata (Chlorophyceae)* and *Prorocentrum micans (Dinophyceae)* : One represents the low absorption case and the other is the high absorption case. The intracellular pigment c_i in two kinds of phytoplankton is assumed to be the same, $2.25\times10^6 mg\cdot m^{-3}$; And the real part of refractive index, n is independent of light wavelength. As an input to Mie calculation, three values of n (relative to water) are used: 1.035, 1.045 and 1.055. The last parameter needed to perform the Mie scattering calculations is particle size distribution, Junge-Type differential size distribution of particles in the open ocean is used:

$$F(D) = KD^{-j} \qquad (12)$$

Here j is the slope of size distribution of particles, and for particles larger than $1 \sim 2\mu m$ in size, the most common exponent value j has been turned out to be around 4. In addition, the other two slopes j are considered: $j = 3.6$ and $j = 4.4$. The smallest particles are assumed to be $0.02\mu m$, and the largest is $200\mu m$.

4 Result and Discussion

4.1 pigment-specific absorption and backscattering coefficient of phytoplankton

The Mie calculation for phytoplankton were performed for different combination of n, n' and j. We assumed that the base phytoplankton model is described by $n = 1.045$ and $j = 4.0$ for low absorption case (low n' case) and high absorption case (high n' case).

The pigment-specific absorption coefficient a^* is obviously higher for high n' case than for low n' case, Fig 1(a), and the effect of n on a^* is very small for both cases of n'; The influence of j on a^* is relatively greater.

The effects of n' on pigment-specific backscattering coefficient, b_b^* is less important than those on a^*. However, b_b^* is very sensitive to the variations in n and j. The effect of size distribution on $b_b^*(\lambda)$ will be greater.

4.2 Variability in ocean **reflectance contributed**

by phytoplankton and mineral

Fig 2 shows the $b_b/(a+b_b)$ ratio for the simple case when phytoplankton and mineral particles with different concentrations are present in seawater only. The optical properties of mineral particles are computed by setting the real part of refractive index, $n=1.18$, and the slope of size distribution, $j=4.0$, and the imaginary part of refractive index satisfies an exponential function $n'(\lambda)=0.010658\exp(-0.007186\lambda)$. There are three concentrations of mineral particles are considered in the model, $C=0.01$, 0.1 and $1.0 g\cdot m^{-3}$ respectively . For the very low concentration of minerals, $C=0.01g\cdot m^{-3}$, the spectral curves of $b_b/(a+b_b)$ for the combination of mineral and seawater are very similar to the curves. But for $C=0.1g\cdot m^{-3}$, the spectral shapes are distinguishable from that for pure seawater.

These analysis results show that (1) reflectance in short wavelength region is more sensitive to the *Chl* variation; (2) when the mineral concentration in seawater is sufficient high, the reflectance spectrum are almost free from the affection of variations of *Chl.*

The similar characterizations are shown in high

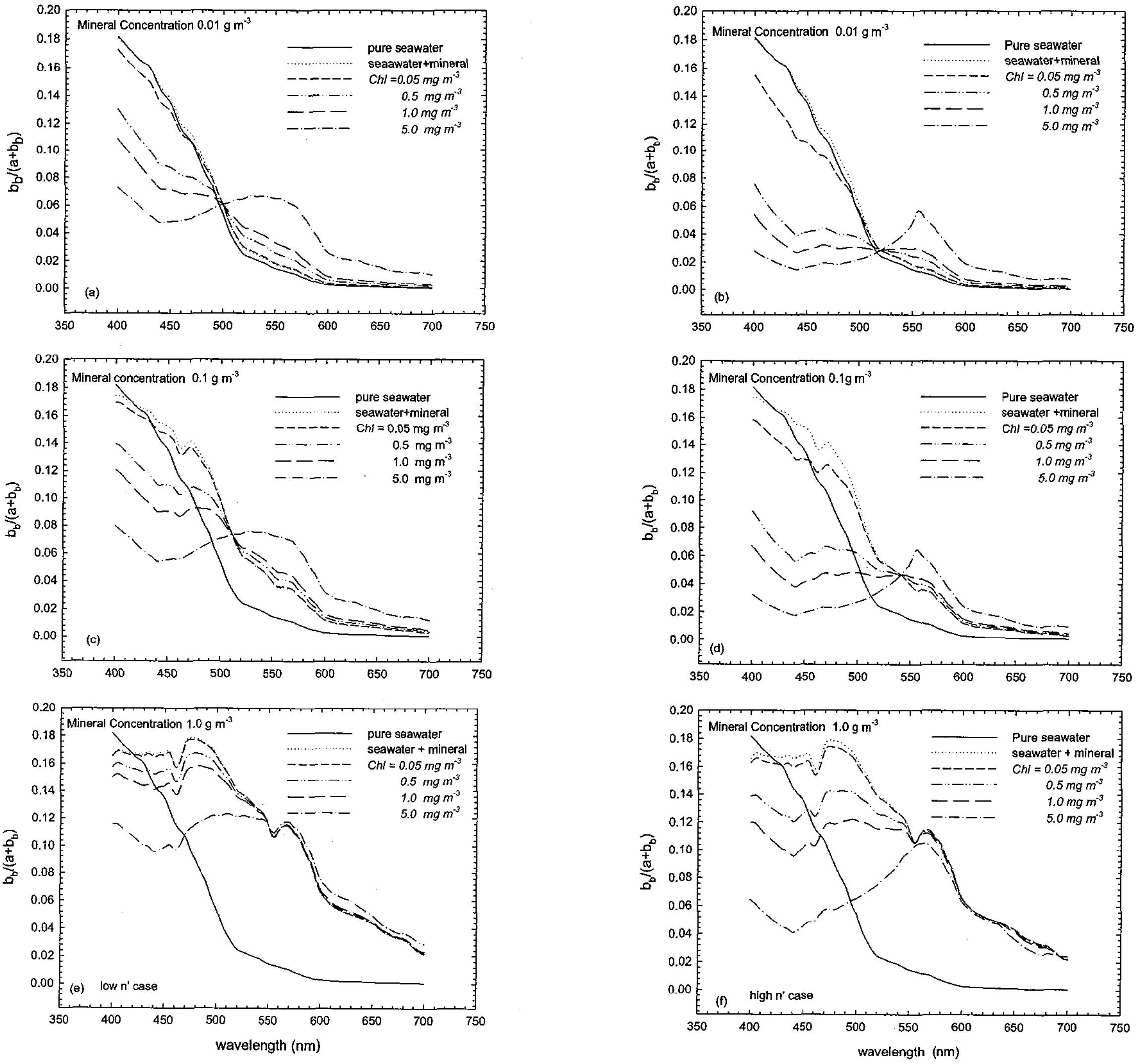

Fig. 2 Spectrum of the $b_b/(a+b_b)$ ratio for various cases when phytoplankton at different *Chl* is mixed with different concentrations of mineral for $0.01 g\cdot m^{-3}$ [(a) and (b)], and $0.1 g\cdot m^{-3}$ [(c) and (d)], and $1.0 g\cdot m^{-3}$ [(e) and (f)]. The mineral particles are characterized by the slope of size distribution, $j=4.0$, and the real part of refractive index, $n=1.18$, the imaginary part $n'(\lambda)=0.010658\exp(-0.007186\lambda)$. The left-hand panels are for low n' case, and the right-hand panels are for the high n' case. The solid curves represent pure seawater.

n' case, and the corresponding values of $b_b/(a+b_b)$ are lower in high n' case than those in low n' case.

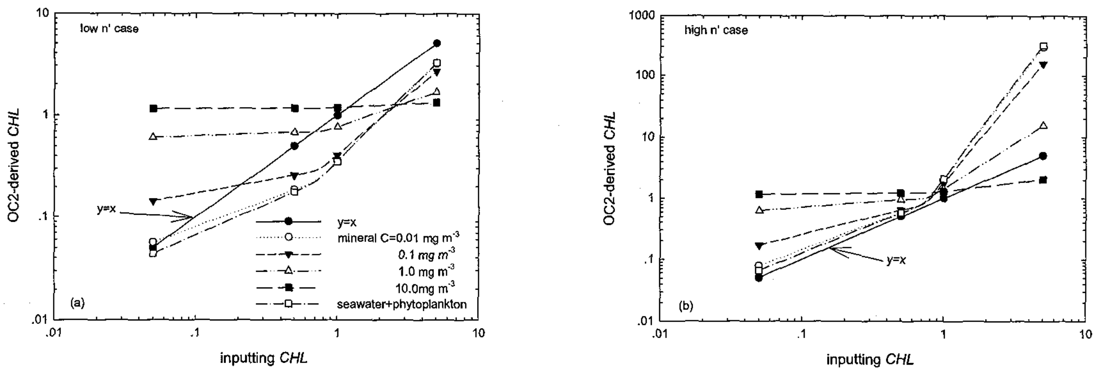

Fig 3 the comparison between the *Chl* estimated from the OC2 algorithm and the *Chl* inputting into the model when different mineral particle concentration are considered. (a) is for phytoplankton with low n' case ; and (b) is for phytoplankton with high n' case. The parameters for mineral particles are the same as those in Fig. 2.

Next, for testing the influence of mineral particles on the Chlorophyll estimations from ocean color, the OC2-derived *Chl* are compared with *Chl* actually inputting into the computation of $b_b/(a+b_b)$ (Fig. 3).

The *Chl* estimated from OC2 algorithms indicates that the existence of mineral particles affects the Chlorophyll estimation. When the inputting Chlorophyll concentration is 0.05 $mg \cdot m^{-3}$, the accuracy of Chlorophyll estimation from OC2 algorithms will decrease greatly with the increasing concentration of mineral particles. And when the mineral concentration is sufficient enough, the Chlorophyll estimation from OC2 only has a little change. It indicates that sufficient concentration at mineral particles in seawater will cover up the real information of Chlorophyll. Meanwhile, with the increase of chlorophyll concentration, the accuracy of estimation will also decrease. In addition, by comparing OC2-derived *Chl* in low n' case and high n' case [Fig 3(a) and 3(b)], we found that, under the same inputting chlorophyll concentration, the OC2-derived *Chl* exist the obvious differences, and these differences will increase with the increase of inputting *Chl*. This indicates that OC2 algorithms ignoring the difference between algae itself will also cause the mistake in *Chl* estimation.

5 Conclusions

Given a simple case, the phytoplankton and mimeral particles are the only constituents in seawater.

The chlorophyll estimation from OC2 algorithm may affected by the existence of mineral particles. With the increase in the mineral concentration, the accuracy of Chlorophyll estimation from OC2 algorithms will decrease greatly. And sufficient concentration at mineral particles in seawater will cover up the real information of Chlorophyll. In addition, OC2 algorithms ignoring the difference between algae itself may also result in the mistake in *Chl* estimation.

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