

Chlorophyll-based model of seawater optical properties

Vladimir I. Haltrin

A one-parameter model of the inherent optical properties of biologically stable waters is proposed. The model is based on the results of *in situ* measurements of inherent optical properties that have been conducted at different seas and oceans by a number of researchers. The results of these investigations are processed to force this model to agree satisfactorily with an established regression model that connects the color index with the chlorophyll concentration. The model couples two concentrations of colored dissolved organic matter (concentrations of humic and fulvic acids) and two concentrations of suspended scattering particles (concentrations of terrigenous and biogenic particles) with the chlorophyll concentration. As a result, this model expresses all inherent properties of seawater by a single parameter, the concentration of chlorophyll.

OCIS codes: 010.000, 010.160, 010.200, 060.210, 060.220, 290.150.

1. Introduction

I describe a one-parameter model of inherent optical properties for biologically stable (BioSt) seawater.^{1,2} The working definition for biologically stable waters includes all case 1 and those case 2 waters in which clay, quartz, and detritus are absent. The idea of deriving a one-parameter model arose from the observation that the majority of *in situ* measurements of inherent optical properties have significant cross correlations for waters that fit the BioSt criterion. As a consequence of the cross correlation of all the inherent optical properties, we can choose any parameter as a measure for all the optical properties. This fact was utilized by the remote-sensing community by use of color indices (or ratios of upwelling irradiances) to estimate subsurface chlorophyll content.

The model is based on the results of *in situ* measurements of inherent optical properties that were conducted on different seas and oceans by Carder *et al.*,³ Clark *et al.*,⁴ Kopelevich,⁵ and Prieur and Sathyendranath.⁶ The pure water optical properties are taken from Pope and Fry⁷ and Morel and Prieur.⁸ The results of these investigations are processed with radiative-transfer simulations to force this model to agree satisfactorily with a regression between the color index and the chlorophyll concentration pro-

posed by Morel and Gordon.^{9,10} The resulting model couples two concentrations of colored dissolved organic matter (concentrations of humic and fulvic acids) and two concentrations of suspended scattering particles (concentrations of terrigenous and biogenic suspensions) with the chlorophyll content in the 0–12-mg/m³ range.

The model is tested on the independently derived regression, based on experimental data by Timofeyeva,¹¹ that connects the diffuse attenuation coefficient with the single-scattering albedo. For the range of chlorophyll concentrations between 0 and 12 mg/m³ considered here, the match is in the range of experimental error, i.e., ~10%.

2. Model of Seawater Optical Properties

From an optical point of view, seawater is an absorbing and scattering medium. Light energy that propagates in water is absorbed by water molecules and dissolved organic matter (DOM) or a yellow substance or gelbstoff. Propagating light is also elastically scattered by thermal fluctuations in water (Rayleigh scattering) and by hydrosol particles suspended in water.^{12,13} The major portion of absorbed energy is transformed into heat. The rest of the absorbed energy is reemitted as Raman scattering and fluorescence.^{14–17} Elastic scattering occurs without a change in energy; only the direction of propagation changes.

All the optical properties of seawater are divided into two groups: inherent and apparent. Inherent optical properties depend only on the processes of absorption and single scattering in seawater.^{18,19} Apparent optical properties depend on inherent opti-

The author is with the Ocean Sciences Branch, Code 7331, Naval Research Laboratory, Stennis Space Center, Mississippi 39529-5004. His e-mail address is haltrin@nrlssc.navy.mil.

Received 12 April 1999; revised manuscript received 20 July 1999.

cal properties, geometry of illumination, and processes of transmission and reflection by the sea surface and sea bottom.¹²

There are only two principal inherent optical properties: an absorption coefficient a and an angular scattering coefficient $\beta(\vartheta)$ (here ϑ is a scattering angle).²⁰ All other inherent optical properties are functions of a and $\beta(\vartheta)$ including the phase function of scattering, $p(\vartheta) \equiv \beta(\vartheta)/b$; the scattering coefficient

$$b = 0.5 \int_0^\pi \beta(\vartheta) \sin \vartheta d\vartheta;$$

the beam attenuation coefficient, $c = a + b$; the single-scattering albedo, $\omega_0 = b/c$; the probability of backscattering,

$$B = 0.5 \int_{\pi/2}^\pi p(\vartheta) \sin \vartheta d\vartheta \equiv b_B/b;$$

the backscattering coefficient, $b_B = bB$; and Gordon's parameter,

$$g = \omega_0 B / (1 - \omega_0 + \omega_0 B) \equiv b_B / (a + b_B).$$

The model presented here has been constructed and tested for more than a decade.^{12,13,15,17} It represents a unified representation of time-proved results that have been published by several researchers.^{3-15,21-29}

A. Model of Absorption

The absorption model is based on chlorophyll concentration and two components of a yellow substance: fulvic and humic acids. The splitting of the yellow substance on two components is practically justified for two reasons. First, it makes this model universal for all biologically stable (i.e., case 1 and parts of case 2) waters. Second, it permits models in the future to include effects of fluorescence by DOM in a more consistent manner.

The absorption coefficient $a(\lambda)$ (m^{-1}) of seawater is taken to be^{30,31}

$$a(\lambda) = a_w(\lambda) + a_c^0(\lambda)(C_c/C_c^0)^{0.602} + a_f^0 C_f \exp(-k_f \lambda) + a_h^0 C_h \exp(-k_h \lambda), \quad (1)$$

where $a_w(\lambda)$ is the pure water absorption coefficient in inverse meters, λ is the vacuum wavelength of light in nanometers, $a_c^0(\lambda)$ is the specific absorption coefficient of chlorophyll in inverse meters, C_c is the total concentration of chlorophyll in milligrams per cubic meter ($C_c^0 = 1 \text{ mg/m}^3$), $a_f^0 = 35.959 \text{ m}^2/\text{mg}$ is the specific absorption coefficient of fulvic acid (the first component of DOM); $k_f = 0.0189 \text{ nm}^{-1}$; $a_h^0 = 18.828 \text{ m}^2/\text{mg}$ is the specific absorption coefficient of humic acid (the second component of DOM); $k_h = 0.01105 \text{ nm}^{-1}$; C_f and C_h are concentrations of fulvic and humic acids, respectively, in milligrams per cubic meter. The values for $a_w(\lambda)$ and $a_c^0(\lambda)$ are in Refs. 6 and 7, and the values for DOM components are in Refs. 3 and 14.

B. Model of Scattering

The scattering model is adopted from the research of Kopelevich.⁵ (This important research has never been translated into English.) Some fragments of this scattering model may be found in Refs. 12, 15-17, and 32. The Kopelevich scattering model is a result of extensive optical measurements taken in the Atlantic, Pacific, and Indian oceans and surrounding seas by researchers at the Shirshov Institute of Oceanology. This model couples an angular scattering coefficient of seawater with concentrations of two fractions of marine hydrosol. The first fraction consists of large organic particles with a refractive index equal to 1.03 and density $\rho_l = 1 \text{ g/cm}^3$. The second fraction consists of small terrigenous particles³³ with a refractive index equal to 1.15 and density $\rho_s = 2 \text{ g/cm}^3$.

The scattering $b(\lambda)$ and backscattering $b_B(\lambda)$ coefficients are calculated according to Refs. 5, 12, and 15-17:

$$b(\lambda) = b_w(\lambda) + b_s^0(\lambda)C_s + b_l^0(\lambda)C_l, \quad (2)$$

$$b_B(\lambda) = 0.5b_w(\lambda) + B_s b_s^0(\lambda)C_s + B_l b_l^0(\lambda)C_l, \quad (3)$$

where

$$B_s = 0.5 \int_{\pi/2}^\pi p_s(\vartheta) \sin \vartheta d\vartheta = 0.039,$$

$$B_l = 0.5 \int_{\pi/2}^\pi p_l(\vartheta) \sin \vartheta d\vartheta = 6.4 \times 10^{-4}, \quad (4)$$

B_s is the probability of backscattering by small particles, B_l is the probability of backscattering by large particles, $b_w(\lambda)$ is the scattering coefficient by pure water in inverse meters, $b_s^0(\lambda)$ and $b_l^0(\lambda)$ are, respectively, the specific scattering coefficients in square meters per gram for small and large particulate matter; C_s and C_l are, respectively, concentrations in grams per cubic meters of small and large particles. The equation for $b_w(\lambda)$ is derived by interpolating the data published by Morel and Prieur⁸:

$$b_w(\lambda) = 0.005826(\text{m}^{-1}) \left(\frac{400}{\lambda} \right)^{4.322}. \quad (5)$$

The spectral dependencies for scattering coefficients of small and large particulate matter are given by^{5,12}

$$b_s^0(\lambda) = 1.151302 (\text{m}^2/\text{g}) \left(\frac{400}{\lambda} \right)^{1.7}, \quad (6)$$

$$b_l^0(\lambda) = 0.341074 (\text{m}^2/\text{g}) \left(\frac{400}{\lambda} \right)^{0.3}. \quad (7)$$

Expressions for the phase functions of scattering by small and large particles, $p_s(\vartheta)$ and $p_l(\vartheta)$, are given below.

The phase function of scattering was derived earlier by Kopelevich⁵ from results of *in situ* measurements and modeling calculations. This phase

Table 1. Coefficients of Eqs. (9) for the Two Basic Phase Functions p_s and p_l

n	1	2	3	4	5
s_n	-2.957089×10^{-2}	-2.782943×10^{-2}	1.255406×10^{-3}	-2.155880×10^{-5}	1.356632×10^{-7}
l_n	-1.604327	8.157686×10^{-2}	-2.150389×10^{-3}	2.419323×10^{-5}	-6.578550×10^{-8}

function was proposed in tabular form⁵ as part of a physical model of light scattering in seawater. The Kopelevich model expresses the total hydrosol scattering function as a linear combination of two phase functions, p_s and p_l . The phase function p_s describes scattering by a small terrigenous fraction of particles. The phase function p_l describes scattering by large particles associated with a biogenic fraction of marine hydrosol (phytoplankton). The total hydrosol angular scattering coefficient is expressed as

$$\beta_H(\lambda, \vartheta) = b_s^0(\lambda)p_s(\vartheta)C_s + b_l^0(\lambda)p_l(\vartheta)C_l. \quad (8)$$

The small- and large-component phase functions in Eq. (8) can be expressed by the following regressions derived in Ref. 21: **(corrected 8/14/00)**

$$p_s(\vartheta) = 52.39389 \exp\left(\sum_{n=1}^5 s_n \vartheta^{3n/4}\right),$$

$$p_l(\vartheta) = 7653.704 \exp\left(\sum_{n=1}^5 l_n \vartheta^{3n/4}\right), \quad (9)$$

where ϑ is the scattering angle in degrees. The coefficients s_n and l_n are given in Table 1.

The seawater angular scattering coefficient is a linear combination of a Rayleigh phase function of scattering p_R and hydrosol phase functions p_s and p_l :

$$\beta(\lambda, \vartheta) = b_w(\lambda)p_R(\vartheta) + b_s^0(\lambda)p_s(\vartheta)C_s + b_l^0(\lambda)p_l(\vartheta)C_l, \quad (10)$$

$$p_R(\vartheta) = 0.7823 + 0.6531 \cos^2 \vartheta. \quad (11)$$

Equations (1)–(11) permit us to compute inherent optical properties of seawater a , b , b_B , and $\beta(\lambda, \vartheta)$ as functions of wavelength and five concentrations, C_c , C_h , C_f , C_s , C_l , of dissolved and suspended matter.

3. Relationships between Concentrations

Results of *in situ* measurements of BioSt seawater optical properties show that in a majority of cases any two formally independent optical properties correlate with each other. In laboratory experiments and *in situ* measurements by Timofeyeva,^{11,22–25} the diffuse attenuation coefficient correlates with the single-scattering albedo and the diffuse reflection coefficient. Processing all Petzold phase functions^{21,26} shows that the parameters of these phase functions correlate with a scattering coefficient and a single-scattering albedo. In Morel and Gordon^{9,10} the following correlation is proposed to estimate the chlorophyll concentration C_c in the upper ocean layer:

$$C_r = 1.92I_c^{1.8}, \quad I_c = \frac{R(550)}{R(440)}, \quad (12)$$

where $R(\lambda)$ is a diffuse reflectance at wavelength λ . All these dependencies indicate that we can choose a single parameter to characterize all inherent optical properties. The optical model given by Eqs. (1)–(11) depends on five parameters: C_c , C_h , C_f , C_s , C_l . A one-parameter model implies that we can express any four of these concentrations through a chosen fifth one. It is convenient to choose the chlorophyll concentration C_c as our main parameter. To derive four dependencies that express four concentrations, C_h , C_f , C_s , C_l , through a chlorophyll concentration C_c we minimized the following five-dimensional functional:

$$\Delta(C_c, C_f, C_h, C_s, C_l) = |C_c - C_r|$$

$$\equiv \left| C_c - 1.92 \left[\frac{R_\infty(550)}{R_\infty(440)} \right]^{1.8} \right|. \quad (13)$$

The dependence of $R = R_\infty$ on a and b_B in Eq. (13) is taken from Eq. (64) of Ref. 13. Two stabilizing relationships, $C_h/(C_h + C_f) = 0.1$ (Refs. 3 and 14) and $C_s + C_l = 0.5C_c^{0.75}$ (Ref. 4), were used to restrict a number of solutions. The statistical software package Data Desk was used to solve this problem. For chlorophyll concentrations in the range of $0 \leq C_c \leq 12 \text{ mg/m}^3$ a number of solutions have been found. The nonphysical solutions were discarded [see Figs. 1(b)–1(d)]. The single physically meaningful solution

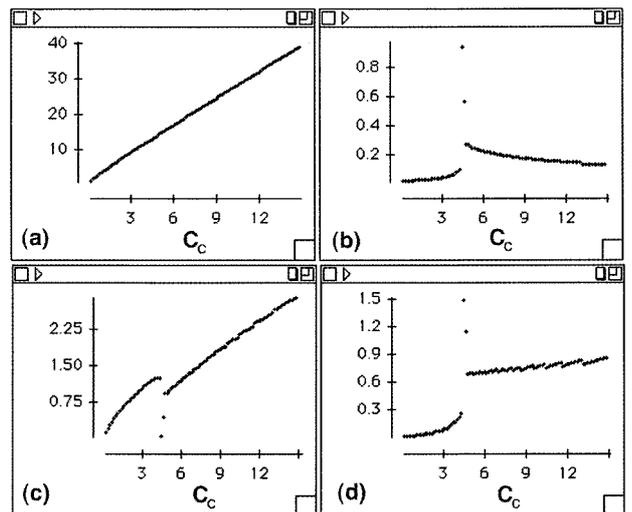


Fig. 1. Cases of (a) physical and (b)–(d) nonphysical solutions to Eq. (13). The physical solution should be monotonous, and its derivative should not have infinitely large spikes.

[Fig. 1(a)] to this problem is presented in the form of four dependencies:

$$\begin{aligned} C_f &= 1.74098C_c \exp[0.12327(C_c/C_c^0)], \\ C_h &= 0.19334C_c \exp[0.12343(C_c/C_c^0)], \\ C_s &= 0.01739(\text{g/mg})C_c \exp[0.11631(C_c/C_c^0)], \\ C_l &= 0.76284(\text{g/mg})C_c \exp[0.03092(C_c/C_c^0)], \end{aligned} \quad (14)$$

where $C_c^0 = 1 \text{ mg/m}^3$; C_c , C_f , and C_h are measured in milligrams per cubic meters; and C_s and C_l are measured in grams per cubic meter. Equations (14) allow us to calculate concentrations of dissolved organic matter (C_f , C_h) and concentration of particles (C_s , C_l) through the concentration of chlorophyll C_c . Equations (14) with Eqs. (1)–(11) constitute a one-parameter model of seawater optical properties.

It is possible to explain why components of yellow substance, C_f , C_h , and concentration of large phytoplankton particles C_l , correlate with the chlorophyll concentration C_c . It is not clear why the concentration of small particles C_s should correlate with chlorophyll concentration. In fact, C_s is more likely to be independent of C_c , but its values are so small that its inclusion in the form of Eqs. (14) will cause minor effects on values of inherent optical properties.

To check a consistency of a model the dependence between a color index $I_c(R)$ and chlorophyll concentration C_c was calculated. For the calculation of the color index I_c the following more general equation for diffuse reflectance under combined illumination by Sun and sky have been used^{13,27}:

$$R = \frac{R_\infty + \mu_s q R_s}{1 + \mu_s q}, \quad (15)$$

where

$$\begin{aligned} R_\infty &= \left(\frac{1 - \bar{\mu}}{1 + \bar{\mu}} \right)^2, \quad R_s = \frac{(1 - \bar{\mu})^2}{1 + \bar{\mu} \mu_s (4 - \bar{\mu}^2)}, \\ \bar{\mu} &= \left\{ \frac{a}{a + 3b_B + [b_B(4a + 9b_B)]^{1/2}} \right\}^{1/2}, \\ \mu_s &= [1 - (\cos h_s/n_w)^2]^{1/2}, \end{aligned} \quad (16)$$

where $0 \leq q \leq 10$ is a ratio of illumination by the Sun to the illumination by the sky,^{19,27} h_s is a solar elevation angle, $n_w \approx 4/3$ is the water refractive index. The computations have been made for all ranges of q ; chlorophyll concentrations, $0 \leq C_c \leq 12 \text{ mg/m}^3$; and solar elevation angles, $5^\circ \leq h_s \leq 90^\circ$. The computed regression ideally coincides with the left-hand side of Eqs. (12) and is shown in Fig. 2.

4. Validation

To validate a one-parameter model of seawater optical properties, the following tests have been done:

By use of the presented model and the theory of Ref. 13, linked arrays of a single-scattering albedo and asymptotic diffuse attenuation coefficients were calculated for the range of chlorophyll concentrations, $0 \leq C_c \leq 12 \text{ mg/m}^3$. The computed depen-

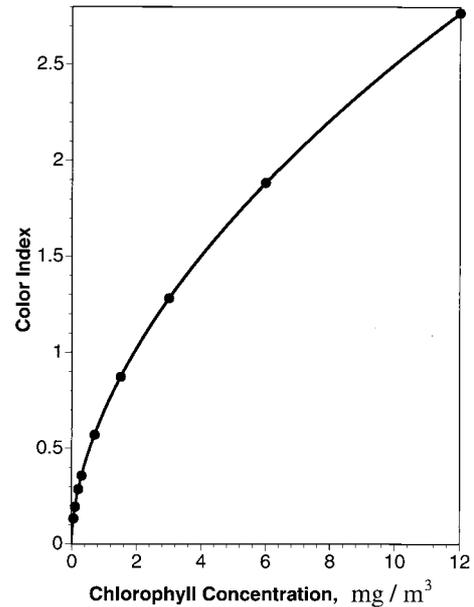


Fig. 2. Regression between the color index, $I_c = R(550)/R(440)$, and the chlorophyll concentration C_c computed for different types of illuminations (each symbol represents 324 close values) compared with the regression $C_c = 1.92I_c^{1.8}$ (solid curve).

dence between the diffuse attenuation coefficient and single-scattering albedo and the similar experimental dependence published by Timofeyeva¹¹ are shown in Fig. 3. These dependencies are close and lie in the range of experimental error.

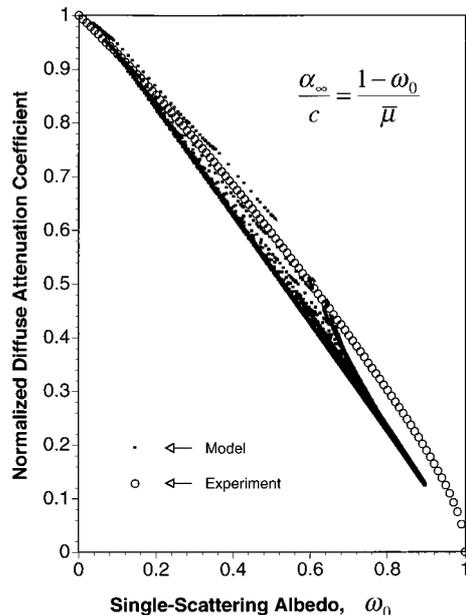


Fig. 3. Relationship between the normalized to the beam attenuation coefficient c asymptotic diffuse attenuation coefficient $\alpha_\infty/c = (1 - \omega_0)/\bar{\mu}$ and the single-scattering albedo ω_0 . The displayed data were computed with the model given by Eqs. (1)–(11) and (14) (14,520 values) and plotted with the experimental data from Ref. 11.

Table 2. Coefficients of Eqs. (19)–(21)

Coefficients \ n	3	2	1	0
σ_{1n}	1.172611×10^{-3}	-2.296292×10^{-3}	2.819422×10^{-2}	2.742180×10^{-2}
σ_{2n}	-3.948394×10^{-2}	7.330175×10^{-2}	-2.627266×10^{-1}	-4.134296×10^{-1}
σ_{3n}	1.172611×10^{-3}	-2.296292×10^{-3}	2.819422×10^{-2}	2.742180×10^{-2}
γ_{1n}	-2.511954×10^{-3}	3.250560×10^{-3}	-2.737673×10^{-3}	2.669329×10^{-3}
γ_{2n}	-1.542883×10^{-4}	3.892168×10^{-4}	-5.757622×10^{-4}	6.662409×10^{-4}
γ_{3n}	1.537038×10^{-5}	-3.169654×10^{-5}	3.058527×10^{-5}	-3.712882×10^{-6}
χ_{1n}	-2.350740×10^1	-2.550000×10^1	3.648087×10^2	3.480213×10^2
χ_{2n}	7.296629×10^3	-2.317441×10^4	-3.961915×10^4	-1.592526×10^4
χ_{3n}	8.962474×10^5	2.983751×10^6	2.247155×10^6	5.654713×10^5
χ_{4n}	-9.223731×10^7	-9.274464×10^7	-4.293989×10^7	-7.874445×10^6

It is possible to conclude now that the presented one-parameter optical model of seawater inherent optical properties gives a good description of optical properties for chlorophyll concentrations as high as 12 mg/m³. It is applicable to the open ocean waters and to the biologically pure coastal waters where inorganic components correlate with chlorophyll content.

5. Relationships between Inherent Optical Properties

A set of coupling equations [Eqs. (14)] between concentrations of seawater species gives a one-parameter model of seawater optical properties. The one-parameter model implies that any fixed inherent optical property may be used as a parameter. For example, if we were to choose a scattering coefficient as such a parameter, we could formulate a one-parameter model of sea optical properties based on a scattering coefficient $b(\lambda)$ at a certain wavelength λ . Let us use Δb , Δb_B , the differences between scattering and backscattering coefficients of seawater and pure water,

$$\Delta b(\lambda) = b(\lambda) - b_w(\lambda), \tag{17}$$

$$\Delta b_B(\lambda) = b_B(\lambda) - 0.5b_w(\lambda), \tag{18}$$

as regression parameters, where $b_w(\lambda)$ is given by Eq. (5). In this case the following relationships can be derived:

$$C_c = \Delta b[\sigma_1 + \Delta b(\sigma_2 + \sigma_3 \Delta b)],$$

$$\sigma_j = \sum_{n=0}^3 \sigma_{jn} \left(\frac{\lambda - 500}{500} \right)^n, \quad j = 1, 2, 3, \tag{19}$$

$$b_B = 0.5b_w + \Delta b[\gamma_1 + \Delta b(\gamma_2 + \gamma_3 \Delta b)],$$

$$\gamma_j = \sum_{n=0}^3 \gamma_{jn} \left(\frac{\lambda - 500}{500} \right)^n, \quad j = 1, 2, 3, \tag{20}$$

$$b = b_w + \Delta b_B[\chi_1 + \Delta b_B[\chi_2 + \Delta b_B(\chi_3 + \chi_4 \Delta b_B)]],$$

$$\chi_j = \sum_{n=0}^3 \chi_{jn} \left(\frac{\lambda - 500}{500} \right)^n, \quad j = 1, 2, 3, 4. \tag{21}$$

Equations (19)–(21) are derived and valid for the wavelengths in the interval $380 \leq \lambda \leq 720$ nm. Coefficients σ_{jn} , γ_{jn} , χ_{jn} are in Table 2. Equations (19)–

(21) allow us to derive a chlorophyll concentration C_c and backscattering coefficient b_B for the same wavelengths λ that correspond to the value of b used to derive parameter $\Delta b = b - b_w$. To restore the whole set of spectral and angular optical properties, $a(\lambda)$, $c(\lambda)$, and $\beta(\lambda, \vartheta)$, we should use the approach in Section 2.

Figures 4 and 5 show an example of the restoration of seawater optical properties for $c = 0.2 \text{ m}^{-1}$ and $\lambda =$

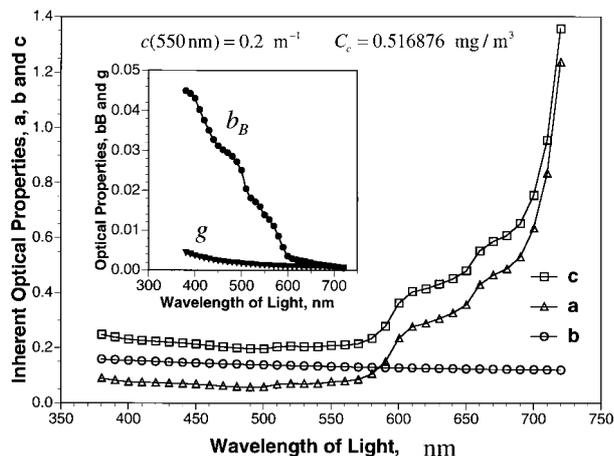


Fig. 4. Example of restored spectral inherent optical properties.

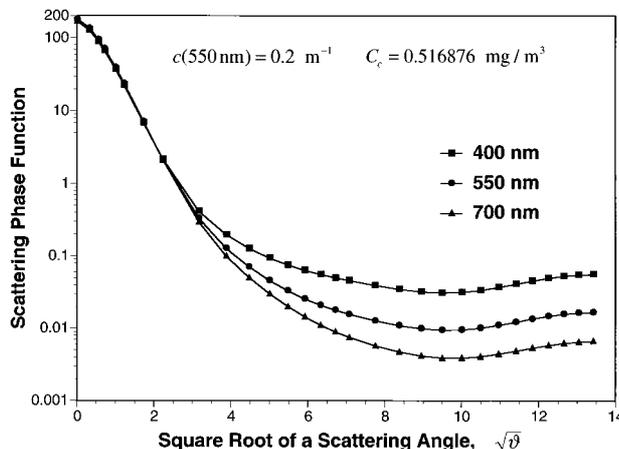


Fig. 5. Example of restored seawater scattering phase functions.

450 nm. The algorithm and Fortran code used to compute the whole set of spectral and angular optical properties with one optical property at one wavelength are in Ref. 34.

6. Conclusion

A one-parameter model of the inherent optical properties of biologically stable waters has been proposed. The model expresses spectral absorption, spectral scattering, and spectral angular scattering coefficients of seawater through the concentration of chlorophyll. The model is based on the results of *in situ* measurements of inherent optical properties that were conducted at different seas and oceans by a number of researchers. The results of these investigations are processed to force this model to agree satisfactorily with the well-known regression $C_c = 1.92I_c^{1.8}$ between the color index I_c and the chlorophyll concentration C_c . The resulting model couples two concentrations of colored dissolved organic matter (concentrations of humic and fulvic acids) and two concentrations of suspended scattering particles (concentrations of terrigenous and biogenic suspensions) with the concentration of chlorophyll.

The model is tested on the independently derived experimental regression, which connects the asymptotic diffuse attenuation coefficient with the single-scattering albedo. For the range of chlorophyll concentrations ($0 \leq C_c \leq 12 \text{ mg/m}^3$) the match is in the range of experimental error. This one-parameter model of seawater optical properties is applicable to the open ocean waters and to the biologically pure coastal waters where organic and inorganic components correlate with chlorophyll content.

This model may be applicable for case 1 waters and part of case 2 waters with optical properties in stable biological equilibrium (BioSt waters). This model is not applicable for case 2 (coastal) waters with a sandy and/or a dirty bottom, especially during several days after stormy weather conditions. To describe such waters some modifications, such as inclusion of scattering by quartz particles,³⁵ should be made.

The author is grateful to Albert W. Green for help and Howard R. Gordon for his suggestion in 1993 to develop such a model. The author also thanks the Naval Research Laboratory (NRL) for continuing support through the programs Littoral Optical Environment 6640-09 and Optical Oceanography 73-5051-09. This paper represents NRL contribution JA/7331-99-0003.

References and Notes

- Some of the material in this paper has been presented at the Ocean Optics XIV Conference, Kailua-Kona, Hawaii, 10–13 November 1998 (see Ref. 2).
- V. I. Haltrin, "One-parameter model of seawater optical properties," in *Ocean Optics XIV CD-ROM* (Office of Naval Research, Washington, D.C., November 1998).
- K. L. Carder, R. G. Stewart, G. R. Harvey, and P. B. Ortner, "Marine humic and fulvic acids: their effects on remote sensing of ocean chlorophyll," *Limnol. Oceanogr.* **34**, 68–81 (1989).
- D. K. Clark, E. T. Backer, and A. E. Strong, "Upwelled spectral radiance distribution in relation to particulate matter in water," *Boundary-Layer Meteorol.* **18**, 287–298 (1980).
- O. V. Kopelevich, "Small-parametric model of the optical properties of seawater," in *Ocean Optics, I: Physical Ocean Optics*, A. S. Monin, ed. (Nauka, Moscow, 1983), pp. 208–234 (in Russian).
- L. Prieur and S. Sathyendranath, "An optical classification of coastal and oceanic waters based on the specific spectral absorption curves of phytoplankton pigments, dissolved organic matter, and other particulate materials," *Limnol. Oceanogr.* **26**, 671–689 (1981).
- R. M. Pope and E. S. Fry, "Absorption spectrum (380–700 nm) of pure water: II. Integrating cavity measurements," *Appl. Opt.* **36**, 8710–8723 (1997).
- A. Morel and L. Prieur, "Analysis of variations in ocean color," *Limnol. Oceanogr.* **22**, 709–722 (1977).
- A. Morel, "In-water and remote measurement of ocean color," *Boundary-Layer Meteorol.* **18**, 177–201 (1980).
- H. R. Gordon and A. Morel, *Remote Assessment of Ocean Color for Interpretation of Satellite Visible Imagery* (Springer-Verlag, Berlin, 1983).
- V. A. Timofeyeva, "Optical characteristics of turbid media of the seawater type," *Izv. Atmos. Ocean Phys.* **7**, 863–865 (1971).
- V. I. Haltrin (aka V. I. Khalturin), "Propagation of light in sea depth," in *Optical Remote Sensing of the Sea and the Influence of the Atmosphere*, V. A. Urdenko and G. Zimmermann, eds. (German Democratic Republic Academy of Sciences Institute for Space Research, Berlin, 1985), Chap. 2, pp. 20–62 (in Russian).
- V. I. Haltrin, "Self-consistent approach to the solution of the light transfer problem for irradiances in marine waters with arbitrary turbidity, depth and surface illumination," *Appl. Opt.* **37**, 3773–3784 (1998).
- S. K. Hawes, K. L. Carder, and G. R. Harvey, "Quantum fluorescence efficiencies of fulvic and humic acids: effect on ocean color and fluorometric detection," in *Ocean Optics XI*, G. D. Gilbert, ed., Proc. SPIE **1750**, 212–223 (1992).
- V. I. Haltrin and G. W. Kattawar, "Effects of Raman scattering and fluorescence on apparent optical properties of seawater," Rep. PH05–1991 (Department of Physics, Texas A&M University, College Station, Tex., 1991).
- V. I. Haltrin and G. W. Kattawar, "Self-consistent solutions to the equation of transfer with elastic and inelastic scattering in oceanic optics: I. Model," *Appl. Opt.* **32**, 5356–5367 (1993).
- V. I. Haltrin, G. W. Kattawar, and A. D. Weidemann, "Modeling of elastic and inelastic scattering effects in oceanic optics," in *Ocean Optics XIII*, S. G. Ackleson and R. Frouin, eds., Proc. SPIE **2963**, 597–602 (1997).
- If we consider these processes on a macroscopic level.
- V. I. Khalturin (aka V. I. Haltrin), "The self-consistent two-stream approximation in radiative transfer theory for the media with anisotropic scattering," *Izv. Atmos. Ocean Phys.* **21**, 452–457 (1985).
- In a general case absorption coefficient a is a function of wavelength λ and sea depth z . The angular scattering coefficient β is a function of wavelength λ , sea depth z , and scattering angle ϑ .
- V. I. Haltrin, "Theoretical and empirical phase functions for Monte Carlo calculations of light scattering in seawater," in *Proceedings of the Fourth International Conference Remote Sensing for Marine and Coastal Environments, I* (Environmental Research Institute of Michigan, Ann Arbor, Mich., 1997), pp. 509–518. [Errata: in Eq. (45) exponent base e should be replaced by 10. In Fig. 3 the vertical label should be: Logarithm (base 10) of Scattering Phase Function.]
- V. A. Timofeyeva, "The diffuse reflection coefficient and its

- relation to the optical parameters of turbid media," *Izv. Atmos. Ocean Phys.* **7**, 467–469 (1971).
23. V. A. Timofeyeva, "Relation between the optical coefficients in turbid media," *Izv. Atmos. Ocean Phys.* **8**, 654–656 (1972).
 24. V. A. Timofeyeva, "Relation between light field parameters and between scattering phase function characteristics of turbid media, including sea water," *Izv. Atmos. Ocean Phys.* **14**, 843–848 (1978).
 25. V. A. Timofeyeva, "Determination of light-field parameters in the depth regime from irradiance measurements," *Izv. Atmos. Ocean Phys.* **15**, 774–776 (1979).
 26. T. J. Petzold, *Volume Scattering Functions for Selected Ocean Waters*, SIO Ref. 72–78 (Scripps Institute of Oceanography, Visibility Laboratory, San Diego, Calif., 1972).
 27. V. I. Haltrin, "Apparent optical properties of the sea illuminated by Sun and sky: case of the optically deep sea," *Appl. Opt.* **37**, 8336–8340 (1998).
 28. V. I. Haltrin, "Diffuse reflection coefficient of a stratified sea," *Appl. Opt.* **38**, 932–936 (1999).
 29. E. Aas, N. K. Hojerslev, and B. Lundgren, "Spectral irradiance, radiance and polarization data from the Nordic cruise in the Mediterranean Sea during June–July 1971," Report 102 (Institutt for Geofysikk, Universitet i Oslo, September 1997).
 30. The explanation of nonlinear dependence on concentration can be found in Ref. 31.
 31. V. I. Haltrin, "Light scattering coefficient of seawater for arbitrary concentrations of hydrosols," *J. Opt. Soc. Am.* **16**, 1715–1723 (1999).
 32. C. D. Mobley, *Light and Water* (Academic, San Diego, Calif., 1994).
 33. K. S. Shifrin, *Physical Optics of Ocean Water* (American Institute of Physics, New York, 1988).
 34. V. I. Haltrin, "An algorithm to restore spectral signatures of all inherent optical properties of seawater using a value of one property at one wavelength," in *Proceedings of the Fourth International Airborne Remote Sensing Conference and Exhibition/21st Canadian Symposium on Remote Sensing*, (Environmental Research Institute of Michigan International, Ann Arbor, Mich., 1999), pp. I-680–I-687.
 35. V. I. Haltrin, E. B. Shybanov, R. H. Stavn, and A. D. Weidemann, "Light scattering coefficient by quartz particles suspended in seawater," in *Proceedings of the International Geoscience and Remote Sensing Symposium IGARSS'99*, T. I. Stein, ed. (Institute of Electrical and Electronics Engineers, Piscataway, N.J., 1999), pp. 1420–1422.

Vladimir I. Haltrin

Chlorophyll based model of seawater optical properties: Erratum & Addendum

to *Applied Optics*, **38**, pp. 6826-6832, (1999).

1. Erratum

The scattering angle ϑ in Eq. (4) and Eq. (9) in Ref. [1] is, correspondingly, regarded as measured in radians and degrees. This may lead to a confusion during integrations. The correctly normalizable version of Eqs. (9) should be:

$$\left. \begin{aligned} p_s(\vartheta) &= 52.39389 \exp\left(\sum_{n=1}^5 s_n \vartheta^{3n/4}\right), \quad \vartheta \text{ in degrees,} \\ p_L(\vartheta) &= 7653.704 \exp\left(\sum_{n=1}^5 l_n \vartheta^{3n/4}\right), \quad \vartheta \text{ in degrees,} \end{aligned} \right\} \quad (1)$$

here s_n and l_n are given in Tab. 1 of Ref. [1]. Equations (1) differs from Eqs. (9) of Ref. [1] by numerical coefficients before exponents. Both phase functions (1) are normalized according to the formula:

$$0.5 \int_0^{\pi} p_i\left(\frac{180}{\pi}\theta\right) \sin\theta d\theta = 1, \quad i = s, l. \quad (2)$$

where θ is in radians. The backscattering probabilities for phase functions given by Eq. (1) are calculated through the following relationship:

$$B_i = 0.5 \int_{\pi/2}^{\pi} p_i\left(\frac{180}{\pi}\theta\right) \sin\theta d\theta, \quad i = s, l. \quad (3)$$

This erratum causes no changes in the conclusions made in Ref. [1]. In the FORTRAN code given in Ref. [2] the following two lines should be corrected: in the function `fpsmall` the line “`fpsmall = 5.61746*EXP(x)`” should be replaced by the line: “`fpsmall = EXP(3.95879 + x)`,” and in the function `fplarge` the line “`fplarge = 188.371*EXP(x)`” should be replaced by the line “`fplarge = EXP(8.942945 + x)`”.

2. Comparison with independently measured experimental data

The code presented in Ref. [2] was used to compare predictions given by the model proposed in Ref. [1] with the experimental values of optical properties measured by Petzold [3] and Mankovsky [4]. The code in Ref. [2] uses as input values of the beam attenuation coefficient $c(\lambda)$ and wavelength of light λ at which it was measured. Figure 1 shows a comparison of restored and actual values of scattering coefficient. The correlation between measured and restored values of scattering coefficient b is strikingly high with the correlation coefficient $r^2 = 0.9941$.

The comparison between restored and measured values of absorption coefficient (See Figure 2) is linear with the correlation coefficient $r^2 = 0.728$. The relatively low regression coefficient here is a result of ignoring absorption by detritus and using specific absorption coefficients by chlorophyll and yellow substances averaged over species.

The comparison of restored and originally calculated values of backscattering probability (see Fig. 3) shows a linear dependence with the proportionality coefficient different from unity:

$$B_{restored} = k_B B_{original}, \quad k_B = 0.337, \quad r^2 = 0.699. \quad (4)$$

Provided that the chlorophyll based model gives excellent predictions for scattering coefficient and acceptable predictions for absorption coefficient and knowing computational methods behind $B_{restored}$ and $B_{original}$ it is possible to explain why k_B in Eq. (4) is not equal to 1.

The phase functions (1) used in chlorophyll-based model [1] are results of Mie calculations of light scattering on a two fractions of scattering particles. The size distributions of these fractions were obtained from analysis of vast experimental data measured by Shirshov Institute of Oceanology. The integration of computed phase functions (1) is done correctly. By integrating experimental phase functions [3, 4] at small angles of scattering both authors used cubic polynomial extrapolation. The Mie scattering calculations show that the realistic phase function may be represented as:

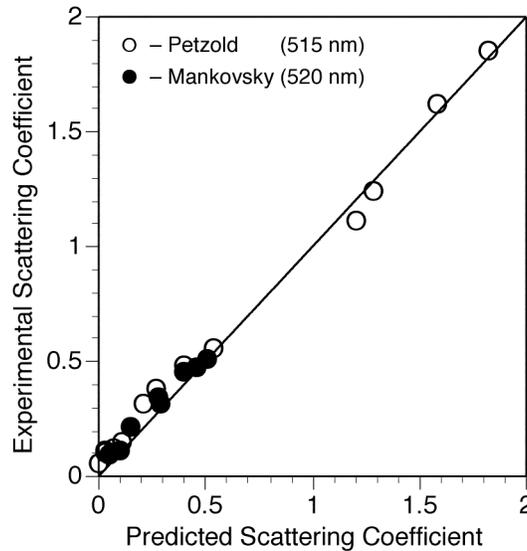


Figure 1. Comparison of measured and predicted scattering coefficients.

$$p(\theta) = \alpha f_{\delta}(\theta) + (1 - \alpha) \tilde{p}(\theta), \quad \{f_{\delta}(\theta) = 0, \quad \theta > \theta_{meas}\}, \quad (5)$$

where $f_{\delta}(\theta)$ is a very narrow highly elongated function, and $\tilde{p}(\theta)$ is a measured phase function. The nephelometers used by Petzold and Mankovsky, due to insufficient angular resolution, failed to measure a phase function fraction proportional to $f_{\delta}(\theta)$. The consequence of this resulted in overestimation of backscattering probability.

Equation (4) may be used to fix experimental phase functions obtained with probes that have insufficient angular resolution. The ‘corrected’ phase function may be represented as:

$$p(\theta) = 0.663 f_{\delta}(\theta) + 0.337 \tilde{p}(\theta), \quad 0.5 \int_0^{\pi} f_{\delta}(\theta) \sin \theta d\theta = 1, \quad 0.5 \int_0^{\pi} \tilde{p}(\theta) \sin \theta d\theta = 1, \quad (6)$$

where $\tilde{p}(\theta)$ is an experimental phase function (like those in Refs. [3-4]) and $f_{\delta}(\theta)$ is an unknown highly anisotropic phase function. For many practical application it is possible to replace $f_{\delta}(\theta)$ by $2\delta(\theta)$ [5], where $\delta(\theta)$ is a Dirac’s delta function. In this case we have the following correction to the experimental phase function $\tilde{p}(\theta)$:

$$p(\theta) = 1.326 \delta(\theta) + 0.337 \tilde{p}(\theta). \quad (7)$$

By correcting experimental data [3,4] with Eq. (7), we obtain:

$$B_{restored} = B_{original}, \quad r^2 \approx 0.7. \quad (8)$$

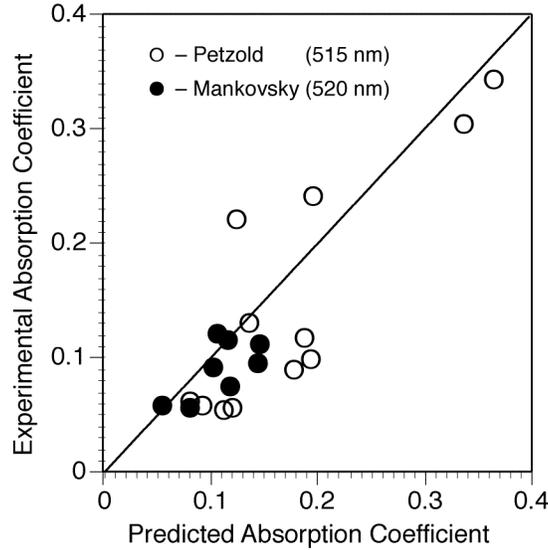


Figure 2. Comparison of experimental and predicted absorption coefficients.

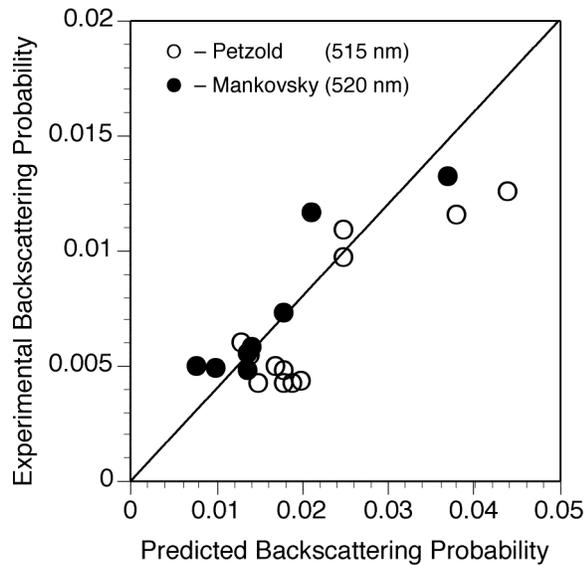


Figure 3. Comparison of estimated from experimental data and predicted probabilities of scattering.

References

1. V. I. Haltrin, "Chlorophyll based model of seawater optical properties," *Applied Optics*, **38**, pp. 6826-6832, (1999).
2. V. I. Haltrin, "An algorithm to restore spectral signatures of all inherent optical properties of seawater using a value of one property at one wavelength," in *Proceedings of the Fourth International Airborne Remote Sensing Conference and Exhibition/21st Canadian Symposium on Remote Sensing*, Published by ERIM International, Inc., Ann Arbor, MI, USA, pp. II-680 -- II 687, (1999), [the latest .pdf version of this article is available on request].
3. T. J. Petzold, *Volume Scattering Functions for Selected Ocean Waters*, SIO Ref. 72-78, (Scripps Institute of Oceanography, Visibility Laboratory, San Diego, CA, 1972).
4. V. I. Mankovsky, private communication, (1996); see also Ref. [5], Eq. 45 and Tab. 5.
5. V. I. Haltrin, "Theoretical and empirical phase functions for Monte Carlo calculations of light scattering in seawater," in *Proceedings of the Fourth International Conference Remote Sensing for Marine and Coastal Environments*, Vol. I, Envir. Res. Inst. of Michigan, Ann Arbor, MI, USA, pp. 509-518, (1997) [the latest .pdf version of this article is available on request].