Modeling of sea optical signatures under natural illumination

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ABSTRACT

The influence of the illumination by the direct sun light and the diffuse light of the sky on the spectral structure of the apparent optical properties of seawater is studied. The resulting formula of this paper couples the sea diffuse reflection coefficient with the angular distribution of the natural light and the inherent optical properties of the seawater. This work uses a self-consistent approach to solve the radiative transfer equation. That approach was developed earlier to calculate the apparent optical properties including the diffuse reflection coefficient. A model of the inherent optical properties of seawater is proposed. This model expresses the inherent optical properties through the concentrations of chlorophyll, yellow substance, and biogenic and terrigenic hydrosols. The transformations of sea optical signatures, due to the changes in illumination and concentrations of suspended and dissolved matter, are analyzed. It is shown that the atmospheric optical parameters and the sun elevation angle significantly influence optical signatures of the upwelling light. The effective wavelength – the parameter that is weakly dependent on the conditions of illumination – is proposed.

Keywords: Optical signatures, diffuse reflection coefficient, natural illumination, radiative transfer, ocean optics, sea optics, optical remote sensing.

1. INTRODUCTION

The studies of spectral signatures of the light ascending from the sea and their dependencies on dissolved and suspended matter in seawater are very important for creation and enhancements of satellite and aircraft algorithms for processing optical information. Precision of analytical expressions that connect apparent optical properties with the inherent ones is also very important for retrieval of concentrations of dissolved and suspended matter in seawater from the optical remote measurements. The diffuse reflection coefficient (DRC) of the sea, the upward and downward diffuse attenuation coefficients are apparent optical properties [1]. They depend not only on the inherent optical properties (absorption and scattering coefficients and phase function of scattering) but also on conditions of illumination of the sea surface. Current algorithms of processing optical remote data usually ignore the dependence of the diffuse reflection coefficient on the conditions of natural illumination. This assumption introduces some systematic error that degrades the precision of the restoration of inherent optical properties from remotely and *in situ* measured apparent optical properties.

The main objective of this paper is to calculate the apparent optical properties of the sea as functions of the inherent optical properties and the parameters of the natural illumination. The spectral and depth variability of the apparent optical properties is also modeled as function of the concentrations of dissolved and suspended matter and the sun elevation angle. This publication is a development of the work accomplished earlier [2-6].

2. BASIC EQUATIONS

Let the homogeneous optically infinitely deep sea be illuminated by the sun elevated at h_s degrees above the horizon and the light of the sky. According to the Snellius law the direct sun rays enter the water at the angle $\cos^{-1}\mu_s$ to nadir, where

$$\mu_s = \sqrt{1 - \cos^2 h_s / n_w^2}, \tag{1}$$

and $n_w \approx 1.34$ is the refraction coefficient of seawater. Let $\overline{L}(z,\mu)$ be the averaged over azimuth radiance of the internal light in the sea that propagates at the angle $\cos^{-1}\mu$ to the $0z$ axis directed from the sea surface to the bottom. Let us introduce

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downward and upward irradiances, E_1, E_2. They are expressed through the averaged radiances by the following formulae:

$$E_1(z) = 2\pi \int_0^1 \overline{L}(z,\mu)\,\mu\,d\mu, \quad E_2(z) = -2\pi \int_{-1}^0 \overline{L}(z,\mu)\,\mu\,d\mu. \tag{2}$$

Let us start from the system of two-flow equations proposed in Refs. [2, 3]:

$$\left.\begin{aligned} \left[\frac{d}{dz} + (2-\overline{\mu})(a+b_B)\right] E_1(z) - (2+\overline{\mu})\, b_B\, E_2(z) &= b_B\, F_s\, e^{-k z/\mu_s}, \\ -(2-\overline{\mu})\, b_B\, E_1(z) + \left[-\frac{d}{dz} + (2+\overline{\mu})(a+b_B)\right] E_2(z) &= b_B\, F_s\, e^{-k z/\mu_s}, \end{aligned}\right\} \tag{3}$$

here F_s is the irradiance by the direct sun light, penetrated into the sea, on the surface that is perpendicular to the sun rays, a is the absorption coefficient, $b_B = b\,B$ is the backscattering coefficient, b is the scattering coefficient, and B is the backscattering probability determined by:

$$B = 0.5 \int_{-1}^{0} p(\mu)\, d\mu, \tag{3a}$$

here $p(\mu)$ is the phase function of scattering on the angle $\cos^{-1}\mu$, [7] and

$$\overline{\mu} = a \quad \sqrt{a + 3b_B + \sqrt{b_B(4a + 9b_B)}}, \tag{4}$$

is an average cosine over irradiance distribution in the sea depth, $k = a + 2\,b_B$. The direct sun illumination is taken into account in Eqns. (3) by the source functions written as right parts of these equations.

The irradiance of the sky diffuse light penetrated into the water is taken into account as boundary condition $E_1(0) = E_0$. The irradiance from the sky just below the sea surface is q times weaker than the irradiance from the sun. Now we have: $F_s = q\,E_0$. Later we define the parameter q as a function of parameters of the atmosphere and the air-water interface.

Let us define the following values. Let $F_s = q\,E_0$ be the portion of the upwelling diffuse irradiance that is originated from the scattering of the sky light penetrated the seawater. Let $E_2^s(z) = E_2(z) - E_2^D(z)$ be the portion of the upwelling irradiance that is originated from the scattering of the sun light.

Now we can introduce the following definitions:

1) The diffuse reflection coefficient of the optically deep ocean illuminated by the diffuse light: $R_\infty = E_2^D(0)/E_1(0)$.

2) The diffuse reflection coefficient of the optically deep ocean illuminated by the sun light: $R_s = E_2^s(0)/(\mu_s\, F_s)$.

3) The diffuse reflection coefficient under combined illumination: $R_c = E_2(0)/(E_0 + \mu_s\, F_s)$. It is connected with R_∞ and R_s by the following formula:

$$R_c = (R_\infty + \mu_s\, q\, R_s)/(1 + \mu_s\, q). \tag{5}$$

Let us seek the solution of the system of Eqns. (3) as the sum of the general and the partial solutions:

$$E_i(z) = A_i \exp(-k_\infty z) + C_i \exp(-k\,z/\mu_s), \quad i = 1,\ 2, \tag{6}$$

here $-k_\infty = -a/\overline{\mu}$ is the negative eigenvalue of the system (3) (the second positive eigenvalue of the Eqns. (3) is $k_0 = 2\,\overline{\mu}\,(a + b_B) + k_\infty$). By inserting Eqn. (6) into Eqns. (3) and applying the boundary condition at $z = 0$, we have:

$$E_i(z) = E_i^D(z) + E_i^s(z), \quad i = 1,\ 2, \quad E_1^D(z) = E_0\, e^{-k_\infty z}, \quad E_2^s(z) = R_\infty E_0\, e^{-k_\infty z}, \tag{7}$$

$$E_1^s(z) = \mu_s\, q\, E_0\, R_0\, (R_2 - R_1)(1 - R_0\, R_\infty)^{-1}\left[e^{-k z/\mu_s} - e^{-k_\infty z}\right], \tag{8}$$

$$E_2^s(z) = \mu_s\, q\, E_0 \left\{ R_2\, e^{-k_\infty z} + \left(R_2 - R_0\, R_\infty R_1\right)\left(1 - R_0\, R_\infty\right)^{-1}\left[e^{-k\, z/\mu_s} - e^{-k_\infty z}\right]\right\}, \tag{9}$$

$$R_\infty = \left[(1-\bar{\mu})/(1+\bar{\mu})\right]^2, \quad R_0 = \left[(2+\bar{\mu})/(2-\bar{\mu})\right] R_\infty, \tag{10}$$

$$R_1 = b_B\left[(1+R_0^{-1})/(k - k_\infty \mu_s)\right], \quad R_2 = b_B\left[(1+R_\infty)/(k + k_\infty \mu_s)\right]. \tag{11}$$

The total downward E_d irradiance should also take into account the irradiance from the direct light:

$$E_d(z) = E_1(z) + \mu_s\, F_s\, e^{-k\, z/\mu_s}, \quad E_u(z) = E_2(z) \tag{12}$$

Summation of Eqns. (7)–(9) gives us the following formulae:

$$E_d(z) = E_0\left\{e^{-k_\infty z} + \mu_s\, q\left[e^{-k\, z/\mu_s} + R_0\left(R_2 - R_1\right)\left(1 - R_0\, R_\infty\right)^{-1}\left(e^{-k\, z/\mu_s} - e^{-k_\infty z}\right)\right]\right\}, \tag{13}$$

$$E_u(z) = E_0\left\{R_\infty\, e^{-k_\infty z} + \mu_s\, q\left[R_2\, e^{-k_\infty z} + \left(R_2 - R_0\, R_\infty R_1\right)\left(1 - R_0\, R_\infty\right)^{-1}\left(e^{-k\, z/\mu_s} - e^{-k_\infty z}\right)\right]\right\}, \tag{14}$$

Let us analyze Eqns. (13)–(14). The value R_1 has a pole at $\mu_s = k/k_\infty = (1+\bar{\mu}^2)/\left[\bar{\mu}\,(3-\bar{\mu}^2)\right]$ and it changes the sign at $\mu_s = k/k_\infty$. By resolving uncertainties at this pole we have:

$$E_d(z) = E_0\left\{1 + \mu_s\, q + b_B\, q\left[(1+R_0)/(1-R_0\, R_\infty)\right] z\right\} e^{-k_\infty z}, \quad \mu_s = k/k_\infty \tag{13a}$$

$$E_u(z) = E_0\left\{R_\infty + \left[b_B\, q\, \bar{\mu}/(2\, a)\right](1+R_\infty) + b_B\, q\, R_\infty\left[(1+R_0)/(1-R_0\, R_\infty)\right] z\right\} e^{-k_\infty z}, \quad \mu_s = k/k_\infty \tag{14a}$$

Equations (13a) and (14a) should be considered when computing apparent optical properties at non zero depth $z \neq 0$. By using introduced definitions and doing some algebra we have the following formula for the diffuse reflection coefficient under directed illumination:

$$R_s = (1-\bar{\mu})^2 \Big/ \left[1 + \mu_s\, \bar{\mu}\,(4-\bar{\mu}^2)\right], \tag{15}$$

here the average cosine $\bar{\mu}$ is determined by the Eqn. (4).

Let us investigate the dependence of diffuse reflection coefficient under combined illumination on the Gordon's parameter $g = b_B/(a+b_B)$, the surface-atmospheric parameter q and the sun elevation angle h_s. Let us introduce some additional auxiliary parameters:

1) The ratio of the diffuse reflection coefficients under directed and diffuse illuminations, $S_R = R_s / R_\infty$:

$$S_R(g) = \left[1+\bar{\mu}(g)\right]^2 \Big/ \left\{1 + \mu_s\, \bar{\mu}(g)\left[4 - \bar{\mu}^2(g)\right]\right\}, \tag{16}$$

here the average cosine can also be expressed as:

$$\bar{\mu}(g) = \sqrt{(1-g)\ \left[1 + 2\, g + \sqrt{g\,(4+5g)}\right]}, \tag{17}$$

2) The relative correction due to the combined illumination, $p = \left(R_c - R_\infty\right)/R_\infty$:

$$p = \left[\mu_s\, q/(1+\mu_s\, q)\right]\left(S_R - 1\right), \tag{18}$$

In this case the diffuse reflection coefficient at combined illumination can be written as:

$$R_c = (1+p)\, R_\infty . \tag{19}$$

The value q in Eqn. (18) depends on atmospheric parameters, the sun elevation angle and characteristics of air-water interface. The value μ_s depends on the sun elevation angle. The value S_R depends on the inherent properties of water and the sun elevation angle.

The inherent optical properties of seawater depend on the content of suspended and dissolved matter, such as, concentration of phytoplankton pigments, concentration of yellow substance and concentrations of scattering particles suspended in water. Fig. 1 shows dependence of Gordon’s parameter g on wavelength of light for three types of seawater that are characterized by the following sets of parameters $\left(C_c, C_y, C_p, \eta\right)$ of the section 3: o – (0.01, 0.22, 0.05, 0.02), m – (0.15, 1.9, 0.2, 0.03), e – (15, 45, 1.5, 0.1).

Fig. 2 shows the spectral dependence of the surface-atmospheric parameter q. The inset in Fig. 2 shows the dependence of parameter q on the sun elevation angle. The values displayed in Figures 1–2 allow us to estimate the range of variability for g and q.

Fig. 3 demonstrates dependence of the parameter S_R on the sun elevation h_s. Fig. 4 displays behavior of parameter $p,\% = 100 \cdot p$ which has the meaning of relative deviation of the diffuse reflection coefficient R_c from the diffuse reflection coefficient under diffuse illumination R_∞. Fig. 5 shows the dependence of the diffuse reflection coefficient R_c on the sun elevation angle h_s. The numbers near the solid curves denote the same sets of parameters (g,q) as used in Fig. 4. Dashed lines correspond to the diffuse reflection coefficient R_∞.

The solutions (13) and (14) of Eqns. (3) allow us to derive equations for a number of apparent optical properties of

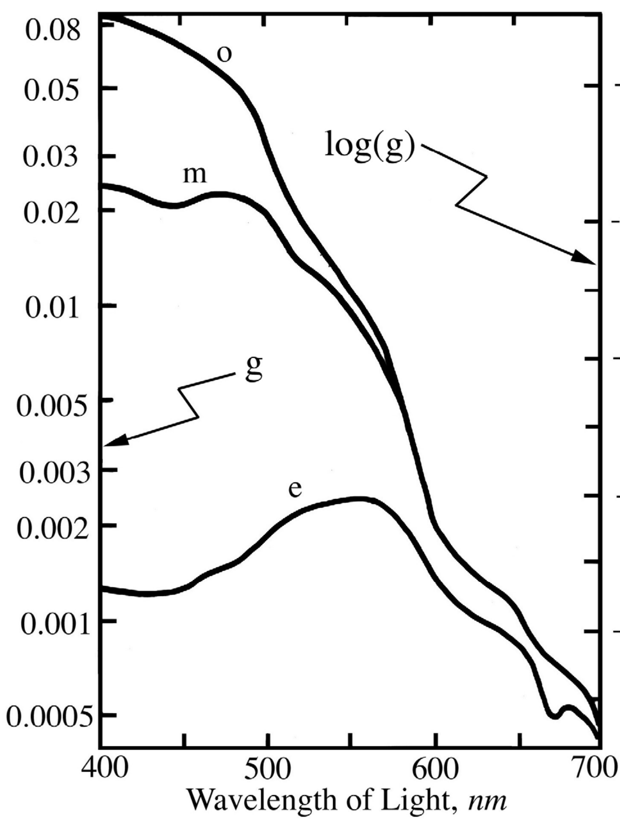

Figure 1. Spectral dependence of Gordon’s parameter g for different water types: o – oligotrophic (open ocean), m – mesotrophic (intermediate waters), e – eutrophic (coastal or littoral waters).

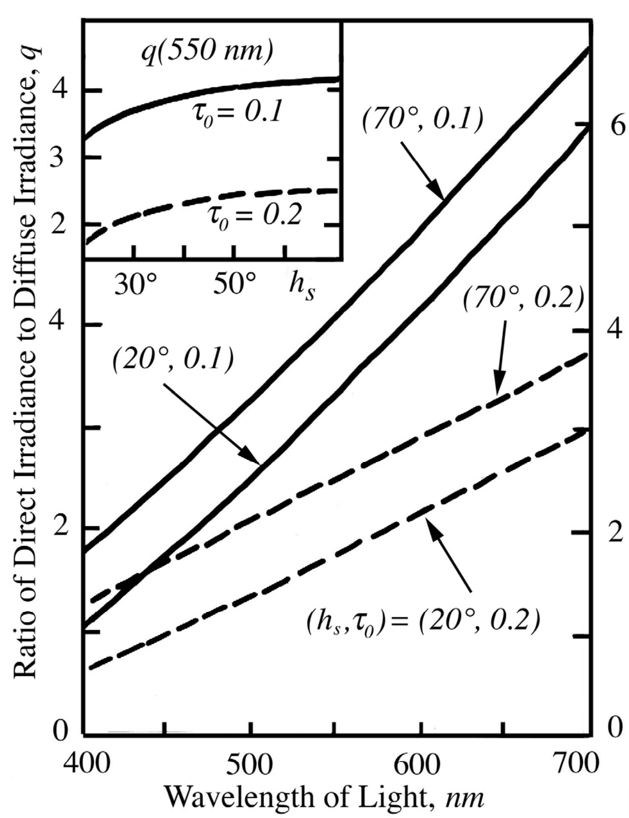

Figure 2. Spectral dependence of the ratio of the direct illumination of the sun to the diffuse illumination of the sky.

homogeneous sea illuminated by the sun and sky:

Transmittance of the layer $0-z$ situated above the horizon $z=$ const.:

$$T(z)=\left[E_1(z)+\mu_s\,F_s\,e^{-kz/\mu_s}\right]\Big/\left(E_0+\mu_s\,F_s\right), \tag{20}$$

Diffuse reflection coefficient measured at depth z:

$$R(z)=E_2(z)\Big/\left[E_1(z)+\mu_s\,F_s\,e^{-kz/\mu_s}\right], \tag{21}$$

Downward diffuse attenuation coefficient at depth z:

$$k_d(z)=-\frac{d}{dz}\log\left\{\left[E_1(z)+\mu_s\,F_s\,e^{-kz/\mu_s}\right]\Big/\left(E_0+\mu_s\,F_s\right)\right\}, \tag{22}$$

Upward diffuse attenuation coefficient at depth z:

$$k_u(z)=-\frac{d}{dz}\log\left\{E_2(z)\Big/\left(E_0+\mu_s\,F_s\right)\right\}, \tag{23}$$

Using Eqns. (13)–(14) and making some simplifications we have:

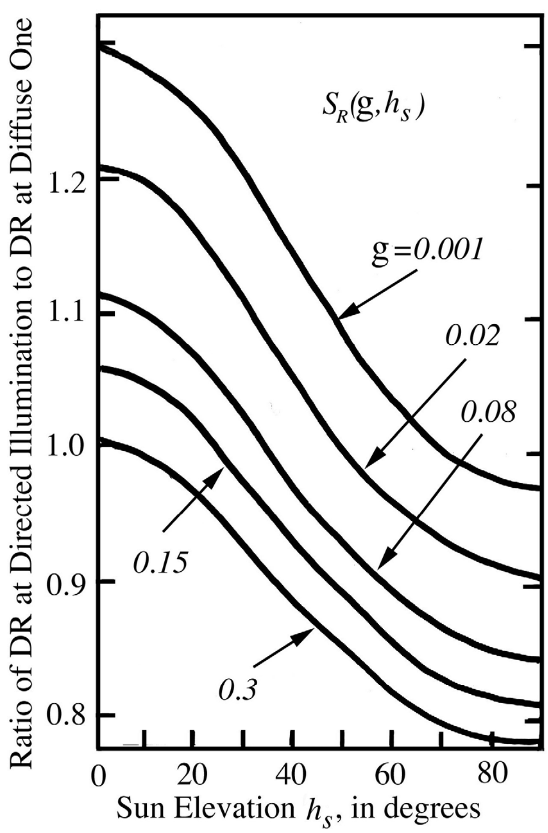

Figure 3. Dependence or the Ratio of DR at directional illumination to the DR at diffuse one on the sun elevation angle for different values of g.

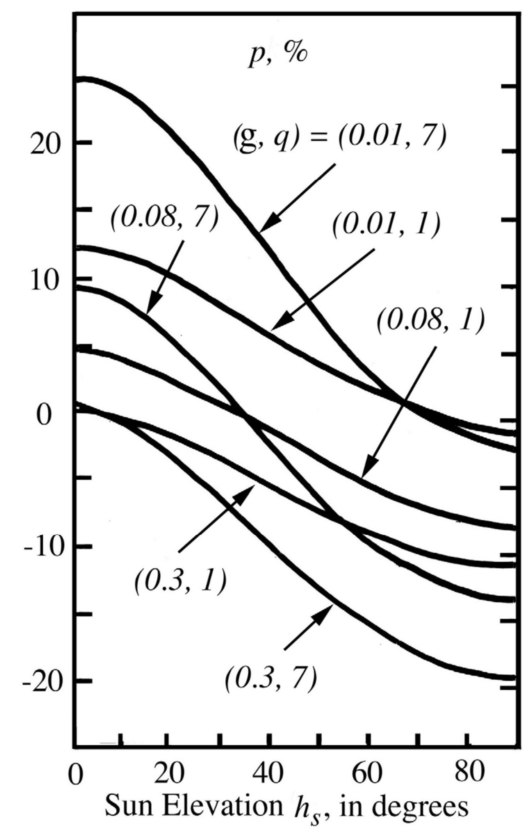

Figure 4. Dependence of the parameter p, relative deviation of R_c from R_∞, on the sun elevation angle for different values of (g,q).

$$T(z) = \left[1 - q_s\,\xi\,\varepsilon(z)\right]\exp(-k_\infty\, z), \tag{24}$$

$$R(z) = \left[R_c - q_s\,\xi\,R_a\,\varepsilon(z)\right] / \left[1 - q_s\,\xi\,\varepsilon(z)\right], \tag{25}$$

$$k_d(z) = k_\infty + q_s\,\xi\left(k/\mu_s - k_\infty\right)\left[1 - \varepsilon(z)\right] / \left[1 - q_s\,\xi\,\varepsilon(z)\right], \tag{26}$$

$$k_u(z) = k_\infty + q_s\,\xi\,R_a\left(k/\mu_s - k_\infty\right)\left[1 - \varepsilon(z)\right] / \left[R_c - q_s\,\xi\,R_a\,\varepsilon(z)\right], \tag{27}$$

here

$$q_s = \mu_s\, q/(1 + \mu_s\, q), \tag{28}$$

$$R_a = (R_2 - R_0\, R_1\, R_\infty) / \left[1 + R_0\,(R_2 - R_1)\right], \tag{29}$$

$$\xi = 1 + R_0\,(R_2 - R_1)/(1 - R_0\, R_\infty), \tag{30}$$

$$\varepsilon(z) = 1 - \exp\left\{\left[k_\infty - (k/\mu_s)\right]z\right\} \tag{31}$$

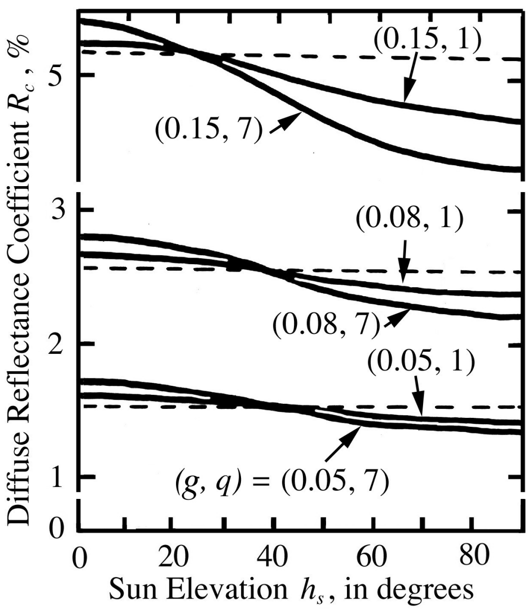

Figure 5. Dependence of DRC under combined illumination on the sun elevation angle (solid lines). Dashed lines are DRC under diffuse illumination, *i.e.*, they represent $R_\infty(g)$.

It is easy to see that the Eqn. (25) like the formula for R_∞ satisfies all limiting conditions at $\bar{\mu} \to 0$ and $\bar{\mu} \to 1$.

At $\mu_s = k/k_\infty$ it is necessary to resolve uncertainties in Eqns. (24)–(27). By introducing additional parameters,

$$q_1 = b_B\, q_s\,(1 + R_0) / \left[\mu_s\,(1 - R_0\, R_\infty)\right] \tag{32}$$

$$\varepsilon_1(z) = \exp(-k\, z/\mu_s) \tag{33}$$

$$\varepsilon_2(z) = \exp(-k_\infty\, z), \quad \varepsilon_3(z) = \varepsilon_1(z) - \varepsilon_2(z), \tag{34}$$

we have:

$$T(z) = \begin{cases} (1 + q_1\, z)\,\varepsilon_2(z), & \mu_s = k/k_\infty, \\ \varepsilon_2(z) + q_s\,\xi\,\varepsilon_3(z), & \mu_s \neq k/k_\infty, \end{cases} \tag{35}$$

$$R(z) = \begin{cases} R_\infty, & \mu_s = k/k_\infty, \\ \dfrac{R_c\,\varepsilon_2(z) + q_s\,\xi\,R_a\,\varepsilon_3(z)}{\varepsilon_2(z) + q_s\,\xi\,\varepsilon_3(z)}, & \mu_s \neq k/k_\infty, \end{cases} \tag{36}$$

$$k_d(z) = \begin{cases} k_\infty - q_1/(1 + q_1\, z), & \mu_s = k/k_\infty, \\ k_\infty + (k/\mu_s - k_\infty)\,\varepsilon_1(z) / \left[\varepsilon_3(z) + \varepsilon_2(z)/(q_s\,\xi)\right], & \mu_s \neq k/k_\infty, \end{cases} \tag{37}$$

$$k_u(z) = \begin{cases} k_\infty - q_1/(1 + p + q_1\, z), & \mu_s = k/k_\infty, \\ k_\infty + (k/\mu_s - k_\infty)\,\varepsilon_1(z) / \left[\varepsilon_3(z) + R_c\,\varepsilon_2(z)/(q_s\,\xi)\right], & \mu_s \neq k/k_\infty. \end{cases} \tag{38}$$

The upward irradiance at depth z, normalized by its value just below the sea surface, is given by the formula:

$$E_u^{(n)} = T(z)\,R(z), \tag{39}$$

At $a\,z >> 1$ the asymptotic depth regime is established. It is characterized by the following diffuse reflection coefficients and attenuation coefficients:

$$R(z)\big|_{k\,z>>1} = \begin{cases} R_\infty\,, & k/\mu_s \ge k_\infty\,, \\ R_a\,, & k/\mu_s < k_\infty\,, \end{cases} \tag{40}$$

$$k_d(z)\big|_{k\,z>>1} = k_u(z)\big|_{a\,z>>1} \approx \min\left(k_\infty\,,\; k/\mu_s\right) = \begin{cases} k_\infty\,, & k/\mu_s \ge k_\infty\,, \\ k/\mu_s\,, & k/\mu_s < k_\infty\,. \end{cases} \tag{41}$$

3. MODEL OF SEAWATER OPTICAL PROPERTIES

From the optical point of view, the seawater is an absorbing and scattering medium. The light energy, that is propagates in water, is absorbed by the water molecules and dissolved organic matter or yellow substance or “Gelbstoff”. At the same time the light is elastically scattered by the water molecules (more exactly, on the thermal fluctuations in water) and by the hydrosol particles (phytoplankton cells, detritus, terrigenic matter) suspended in water. The major portion of absorbed energy is transformed to the heat. The rest of the absorbed energy is re-emitted back with the increase in wavelength (Raman scattering and fluorescence [5, 6]). The elastic scattering occurs without the change in wavelength, only the direction of propagation changes. In the section above, it was shown that in the framework of our approximation the light field in seawater depends on the surface-atmospheric parameter q, the sun elevation angle h_s, and two inherent optical properties: the absorption coefficient a and the backscattering coefficient b_B. Let us consider the dependence of a and b_B on the concentrations of scattering and an absorbing matter in seawater.

3.1 Absorption coefficient

The spectral dependence of the seawater absorption coefficient is expressed as follows:

$$a(\lambda) = a_w(\lambda) + a_c^0(\lambda)\,C_c^{0.602} + a_y^0(\lambda)\,C_y\,, \tag{42}$$

here a_w is the absorption coefficient of seawater [8, 9], a_c^0 is the specific absorption coefficient of phytoplankton pigments in $m^{0.806}/mg^{0.602}$, C_c is the phytoplankton concentration in mg/m^3, [10] a_y^0 is the specific absorption coefficient of yellow substance (as a sum of humic and fulvic acids in ratio of 1 to 9 [11]):

$$a_y^0(\lambda) = \left(0.045\,m^2/mg\right)\exp\left[-0.015(\lambda - 400)\right], \tag{43}$$

C_y is the concentration of the yellow substance in mg/m^3, λ is the wavelength of light in nm.

3.2 Backscattering coefficient

Let us adopt a two-component model of scattering by hydrosol particles [12, 7]. The backscattering coefficient is represented as a sum of the backscattering coefficient by pure water and the backscattering coefficient by hydrosol particles:

$$b_B(\lambda) = b_{Bw}(\lambda) + b_{Bp}^0(\lambda)\,C_p\,, \tag{44}$$

here the backscattering coefficient for pure water is expressed as an approximation of data proposed in Ref. [13]:

$$b_{Bw}(\lambda) = 2.913\cdot 10^{-3}\left(400/\lambda\right)^{4.322}, \tag{45}$$

The backscattering coefficient for the hydrosol particles is a sum of two parts. The first part is the backscattering coefficient for small terrigenic particles. The second one is the backscattering coefficient for large organic particles (phytoplankton and detritus):

$$b_{Bp}^0(\lambda) = \left[8.98\cdot 10^{-2}\left(400/\lambda\right)^{1.7}\eta + 2.183\cdot 10^{-4}\left(400/\lambda\right)^{0.3}(1-\eta)\right](1+\eta)^{-1}, \tag{46}$$

here $C_p = C_s + C_l$, is the total concentration of particles in g/m^3 or mg/l, $C_s = \rho_s v_s$, is the concentration of small terrigenic particles in g/m^3, $C_l = \rho_l v_l$, is the concentration of large particles in g/m^3, $\rho_s = 2\,g/cm^3$, is the density of small particles, $\rho_l = 1\,g/cm^3$ is the density of large particles, v_s and v_l are the volume concentrations of small and large particles in cm^3/m^3, $\eta = v_s/(v_s + v_l)$ is the Kopelevich [12] hydrosol parameter that determines the relative volume share of small particles.

3.3 Scattering coefficient

In the framework of model [12] the scattering coefficient is expressed as:

$$b(\lambda) = b_w(\lambda) + b_p^0(\lambda,\eta)\,C_p, \tag{47}$$

here $b_w(\lambda) = 2\,b_{Bw}(\lambda)$ is the scattering coefficient by pure water, and

$$b_p^0(\lambda,\eta) = \left[2.3(400/\lambda)^{1.7}\,\eta + 0.34(400/\lambda)^{0.3}(1-\eta)\right](1+\eta)^{-1}, \tag{48}$$

is the specific scattering coefficient by hydrosol particles.

Equations (42)–(48) allow us to compute the inherent optical properties of homogeneous sea as the functions of wavelength, three concentrations C_c, C_y, C_p and the hydrosol parameter η. Further we need the beam attenuation coefficient, $c(\lambda) = a(\lambda) + b(\lambda)$, the backscattering coefficient, $b_B(\lambda)$ and the single scattering albedo, $\omega_0(\lambda) = b(\lambda)/c(\lambda)$.

4. MODEL OF ATMOSPHERIC OPTICAL PROPERTIES

To calculate parameter q – that is the ratio of the direct irradiance to the diffuse one – it is possible to use a variety of approaches. Let us use the simple approach proposed originally in Ref. [4]. The irradiance of the flat surface normal to the incident solar rays can be expressed as:

$$F_s(\lambda) = S_0(\lambda)\,T_{oz}(\lambda,\mu_s^a)\exp\left[-\tau(\lambda)/\mu_s^a\right], \tag{49}$$

here S_0 is the spectral solar constant, $\mu_s^a = \sin(h_s)$, $T_{oz} = \exp\left[-\tau_{oz}(\lambda)/\mu_s^a\right]$ is the transmittance by the ozone layer, τ_{oz} is the ozone optical thickness,

$$\tau(\lambda) = \tau_R(\lambda) + \tau_a(\lambda), \quad \tau_R(\lambda) = 0.36(400/\lambda)^{4.086}, \tag{50}$$

is the total optical thickness of the atmosphere, τ_a is the optical thickness of the Rayleigh component of the atmosphere.

The aerosol optical thickness τ_a may be expressed as [4]:

$$\tau_a(\lambda) = t_0 - t_1\,\lambda^{-1} + t_4\,\lambda^{-4}, \tag{51}$$

or through the Ångstrom law [14]:

$$\tau_a(\lambda) = \tau_0\,(\lambda_0/\lambda)^{\alpha_a}, \quad \alpha_a = 0.1/\tau_0, \tag{52}$$

here $\tau_0 \equiv \tau_a(\lambda_0)$ with $\lambda_0 = 745\ nm$. Further we use only a model given by the Eqn. (52).

The irradiance of the sea surface by the diffuse sky light may be represented as follows [4]:

$$E_d^{sky}(\lambda) = S_0(\lambda)\,\mu_s^a\,T_{oz}(\lambda,\mu_s^a)\left\{\left[1+\tau_B(\lambda)/\mu_s^a\right]^{-1} - \exp\left[-\tau(\lambda)/\mu_s^a\right]\right\}, \tag{53}$$

here
$$\tau_B(\lambda) = 0.5\,\tau_R(\lambda) + B_a \tau_a(\lambda), \tag{54}$$

and $B_a = 0.5 - \tau_0$ [14] is the probability of backscattering on aerosol particles.

By taking into account the transmission by the air-water interface, we have:

$$q = F_s(\lambda)/E_0(\lambda) = T(z_s)\,F_s(\lambda)\,/\,T_D\,E_d^{sky}(\lambda), \tag{55}$$

here T_D is the transmission of diffuse light by the air-water interface, $T(z_s) = 1 - R_F(z_s)$ is the transmission of the directed light of the sun with the zenith angle $z_s = \cos^{-1}\mu_s^a \equiv 90° - h_s$, and $R_F(z_s)$ is the Fresnel reflection coefficient of sun light.

After some algebra we have the following formula for the parameter q:

$$q(\lambda, h_s, \tau_0) = \frac{1 - R_F(z_s)}{T_D\,\mu_s^a}\left\{\frac{\exp\left[\tau(\lambda)/\mu_s^a\right]}{1 + \tau_B(\lambda)/\mu_s^a} - 1\right\}^{-1}, \tag{56}$$

Below for the simplicity we will take $\left[1 - R_F(z_s)\right]/T_D \approx 1$ (this assumption introduces a very small error and has no influence on the final precision of computed parameters). We also restrict ourselves to the following three sun elevation angles: h_s =20°, 45°, and 70°.

5. MODELING OF INHERENT AND APPARENT OPTICAL PROPERTIES

To restore inherent optical properties of the ocean from remotely measured optical data we need algorithms of atmospheric corrections. These algorithms remove that portion of the total signal measured from satellite or aircraft which is due to the atmospheric haze. The diffuse reflection coefficient of the sea itself depends on the distribution of light in the atmosphere. Many algorithms neglect this dependence or based on oversimplified two-flow approaches that makes their accuracy unacceptably low.

In the figures below we show the results of computations of apparent optical properties of homogeneous sea based on the approach of sections 1–4. The curves for typical ocean waters that show the significant features of the studied dependencies are plotted.

The spectral dependence of the inherent optical properties a, ω_0, euphotic zone depth d (depth of 1% irradiance) and the asymmetry factor $K = (1-B)/B$ for the three water types are shown on the inset in Fig. 6 and in Fig. 7. In Fig. 6 the spectral dependencies of the diffuse reflection coefficient for the three types of seawater and for the two types of illumination are shown.

The dependencies of diffuse reflection coefficient and the transmission of the water layer on the sun elevation angle are shown in Figs. 8 and 9. These figures show that the main factor in the variability of these apparent optical properties is the sun elevation angle. The dependence on the aerosol optical thickness is insignificant.

Figs. 6 and 9 show that conditions of illumination in some cases influence not only the value but also the shape of the spectral curve. It means the neglecting of this dependence in reverse algorithms may add an additional error to restored optical properties.

It seems quite reasonable to look for such a parameter which is not sensitive to the sun elevation angle and depends mainly on the inherent optical properties of seawater a and b_B (or $g = b_B/(a + b_B)$).

The investigations made in Ref. [15] show that we can choose as such a parameter the value,

$$\lambda_{eff}\left(\lambda_1 \middle| \Phi \middle| \lambda_2\right) \equiv \int_{\lambda_1}^{\lambda_2} \Phi(\lambda)\,\lambda\,d\lambda \Big/ \int_{\lambda_1}^{\lambda_2} \Phi(\lambda)\,d\lambda, \tag{57}$$

named an effective wavelength over a photometric function $\Phi(\lambda)$. As a photometric function $\Phi(\lambda)$ we can choose, for example, a radiance, an irradiance, a diffuse reflection coefficient, an irradiance reflection coefficient, *etc*. The effective wavelength over the radiance or irradiance is reversely proportional to the average energy of the light quantum $\langle \lambda_1 | \varepsilon_\lambda | \lambda_2 \rangle$ in the spectral region between the wavelengths λ_1 and λ_2:

$$\lambda_{eff}\left(\lambda_1 | L | \lambda_2\right) = 2\pi\hbar c_o \Big/ \left\langle \lambda_1 | \varepsilon_\lambda | \lambda_2 \right\rangle, \tag{58}$$

here $\hbar$ is the Planck's constant, c_o is the speed of light in vacuum.

So, the theoretical model presented here, allows to compute λ_{eff} for different water types [16] and lightning conditions. Figs. 10, 11 show a very weak dependence of the effective wavelength $\lambda_{eff}\left(400 | R_c | 700\right)$ on lightning conditions and the very strong correlation of $\lambda_{eff}\left(400 | R_c | 700\right)$ with the chlorophyll concentration C_c. This confirms the recommendations proposed in Ref. [15] to use the effective wavelength as a parameter to classify the optical types of water.

6. CONCLUSION

The approach to calculate apparent optical properties of homogeneous sea illuminated by the direct sun light and the light of the sky is proposed here. This theory is based on the previous works presented in Refs. [2-7]. The experimental results [17] shows the excellent agreement of the previous variant of this theory with the experimental results. To have a correct

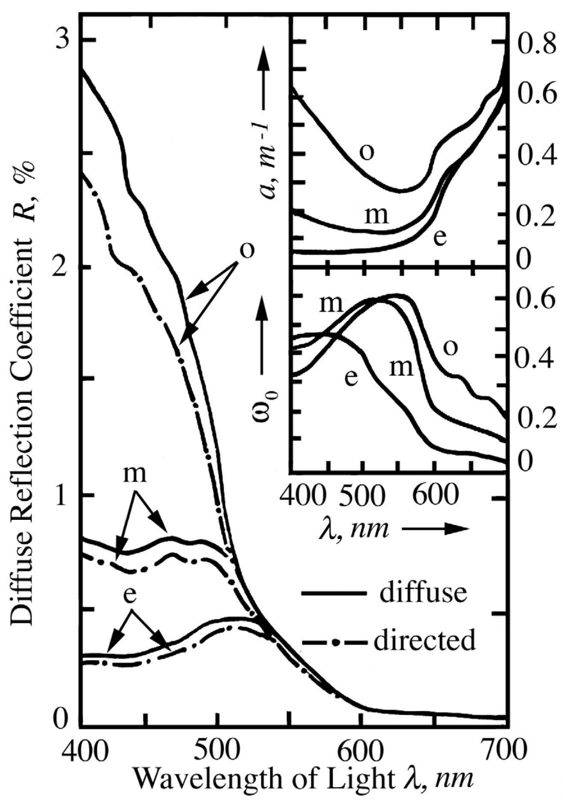

Figure 6. Spectral dependence of diffuse reflection coefficient, absorption coefficient a and single scattering albedo ω_0 for oligotrophic (o), mesotrophic (m) and eutrophic (e) waters. Solid and dashed lines indicate diffuse and direct solar illumination.

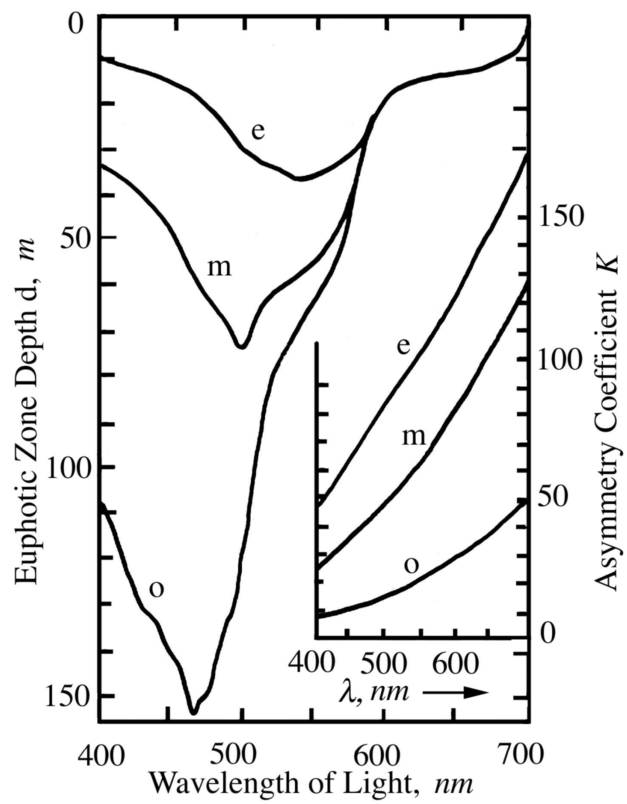

Figure 7. Spectral dependence of the euphotic zone depth d for three types of water: oligotrophic (o), mesotrophic (m), and eutrophic (e).
In the inset: Spectral dependence of the asymmetry parameter $K = (1 - B)/B$.

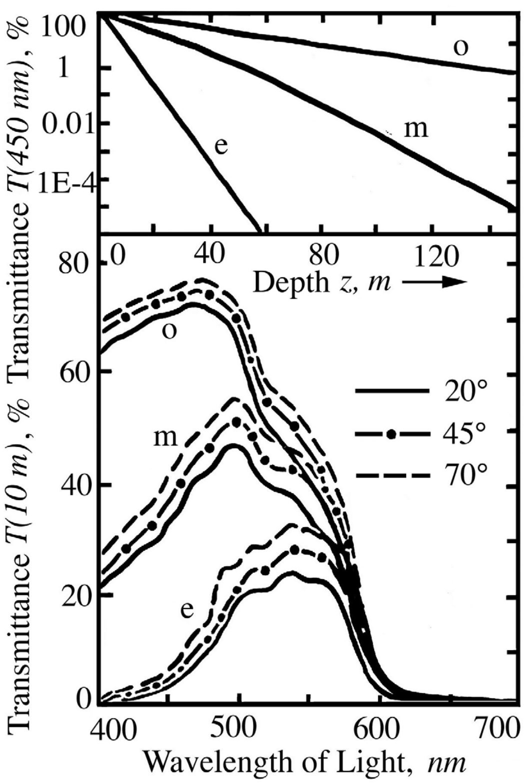

Figure 8. Spectral dependencies of Transmission of the upper 10 *m* layer of the ocean for oligotrophic (o), mesotrophic (m) and eutrophic (e) waters under combined illumination and different sun elevations.

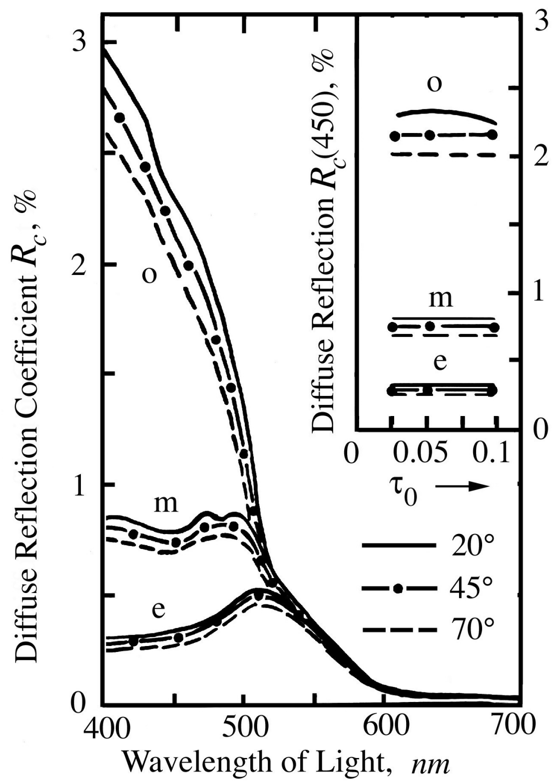

Figure 9. Spectral dependence of the DRC for three water types and different illumination (h_s).
In the inset: Dependence of DRC at 450 *nm* on the atmospheric optical thickness; o, m, e denote water types.

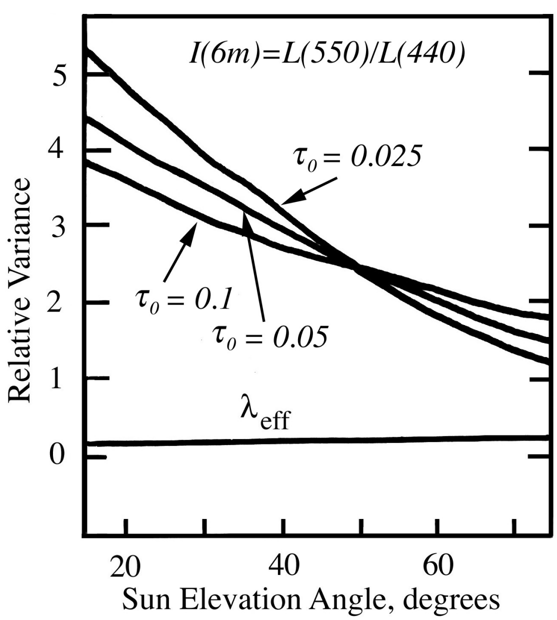

Figure 10. Dependence of relative variance of the color index $I(6m) = L(550) / L(440)$ and effective wavelength on the sun elevation angle.

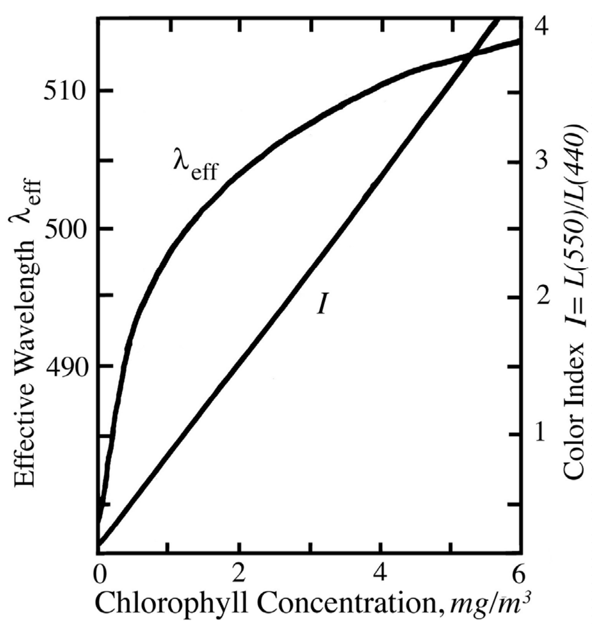

Figure 11. Dependence of the effective wavelength and color index on total concentration of chlorophyll and phaeophytin.

analysis of the experimental optical data it is necessary to fulfill simultaneous measurements of the sun elevation angle and the atmospheric optical parameters. The effective wavelength defined above is a very suitable parameter for description of the sea color: this parameter is not sensitive to the conditions of illumination and it correlates very well with the chlorophyll concentration.

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