Anomalous spectral dependence of backscattering coefficient in water with high phytoplankton concentration

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A technique is proposed to estimate the backscattering coefficient of seawater from measurements of the extinction coefficient along vertical and diffuse reflection coefficient for different types of seawater. The backscatter of light was modeled, and the dependence of the backscattering coefficient on the water type optical index m was obtained.

As known, the spectrum of the radiation upwelling from the sea surface determines the color of seawater and is caused by both light scattering and absorption by the medium. Consequently, solution of the inverse problem on determination of admixture concentrations in the seawater from the brightness of the upwelling radiation requires both these processes to be set parametrically in waters of different productivities. However, these processes are interrelated, and individual contributions of each of them to formation of the upwelling radiation flux can hardly be estimated.[1–6]

In Refs. 7 and 8 it was proposed to assess these processes by measuring simultaneously the characteristics of light field formed in the seawater as a result of joint action of scattering and absorption on the sunlight flux. The vertical extinction coefficient and the diffuse reflection coefficient proved to be sufficient to be taken as such characteristics, especially taking into account that they were extensively measured in the Atlantic, Pacific, and Indian Oceans.[9,10] In Ref. 7 we have proposed and tested the technique for estimating the absorption of light by the seawater from these parameters. In this paper we propose the technique for estimating the light backscattering spectra in water with different content of the main ecological admixtures.

Estimation of backscattering spectra from vertical extinction coefficient and diffuse reflection coefficient in water of different types

As known, the diffuse reflection coefficient R in the two-flux approximation is determined as[1,2]:

$$R = k\beta/(\kappa + \beta) \cong k\beta/\alpha, \qquad (1)$$

where β is the backscattering coefficient; κ is the seawater absorption coefficient; α is the extinction coefficient; k is the empirical coefficient (k is non-selective, and, according to different literature sources, it takes the value from 0.25 to 0.31). Thus, having the spectral characteristics R and α, we can estimate the spectrum of the backscattering coefficient:

$$\beta_\lambda \cong \alpha_\lambda R_\lambda/k. \qquad (2)$$

Let us obtain the spectra of the backscattering coefficient for open-ocean water of different trophic level. Concentrations of the main light-absorbing and light-scattering admixtures in the open ocean, as known, can differ by tens and even hundreds times in different areas. However, the relations between them vary in far more narrow limits, because these admixtures mostly are the products of vital activity of phytoplankton populations and include living plankton, detritus, and dissolved organic matter (yellow substance).[1,2,8] It is just this circumstance that forms the basis for single-parameter classification of water of the World Ocean outside coastal zones by the water type optical index m – positive parameter smoothly varying from unity and above:

$$m = 100 \log e \,|\alpha_{500}| = 43.43\,|\alpha_{500}|, \qquad (3)$$

where $|\alpha_{500}|$ is the dimensionless parameter equal to the vertical extinction coefficient at $\lambda = 500$ nm, in m^{-1}. This classification of open-ocean water was proposed in Refs. 8 and 9. It was also shown there that for waters with close values of m both the spectra of the vertical extinction coefficient and the spectra of the diffuse reflection coefficient differ only slightly.

Analysis of 350 spectra of the vertical extinction coefficient in different regions of the World Ocean, yielded typical values of m to be from 1.15 in the Pacific Ocean near Samoa Islands to 9–11 in the Peruvian Current were obtained, and the rms deviations of the spectral shape from the typical one were estimated.[8] The averaged spectra of the diffuse reflection coefficient of the sea were obtained in a similar way.[8]

Figures 1 and 2 exemplify the spectra of vertical extinction coefficient and diffuse reflection coefficient for waters with m = 1.5, 3, 5, and 8. The first value is characteristic of oligotrophic water, and the last value is characteristic of eutrophic water. The spectra of vertical extinction coefficient has a pronounced evolution with the shift of the minimum toward longer waves, what is caused by the increasing concentration of phytoplankton pigments and dissolved organic matter (DOM), which absorb light in the shortwave part of the visible spectrum. For this same reason, R_λ lowers in the blue spectral region with increasing m.

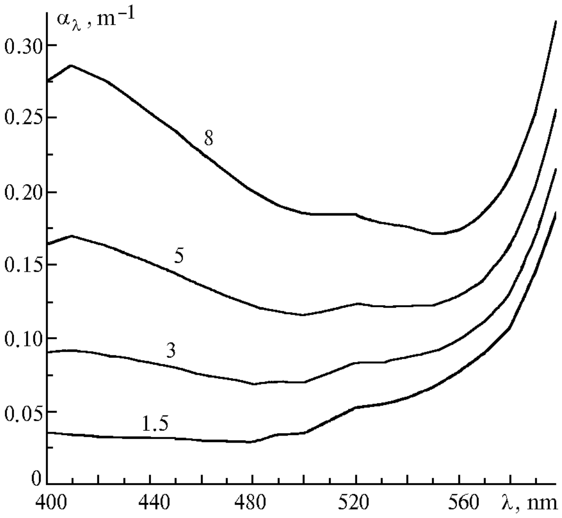

Fig. 1. Spectrum of the vertical extinction coefficient α_λ in waters characterized by different water type index m.

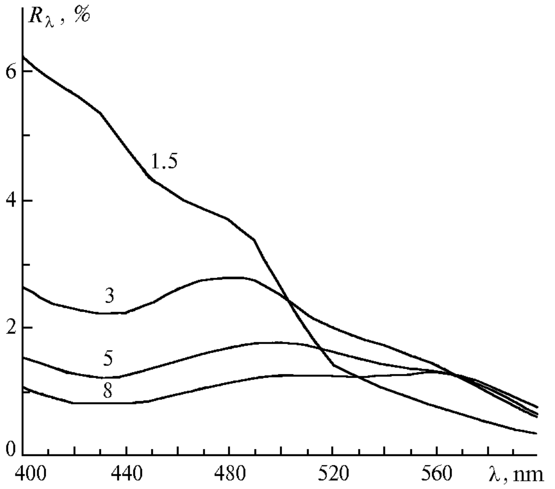

Fig. 2. Spectrum of the diffuse reflection coefficient R_λ in waters characterized by different water type index m.

These data are the initial information for obtaining the spectra of light scattering. The distribution of the water type index m in the World Ocean can be found in Ref. 10. Figure 3 shows the spectra of backscattering coefficient calculated by Eq. (2) for waters with the same values of the water type optical index m.

As is well known, in transparent water it is the Rayleigh molecular scattering that mainly contributes to scattering, whose spectrum is described by the exponential function

$$\beta_m = \beta_{500} (\lambda_0/\lambda)^{4.3}, \quad (4)$$

where λ_0 =500 nm.

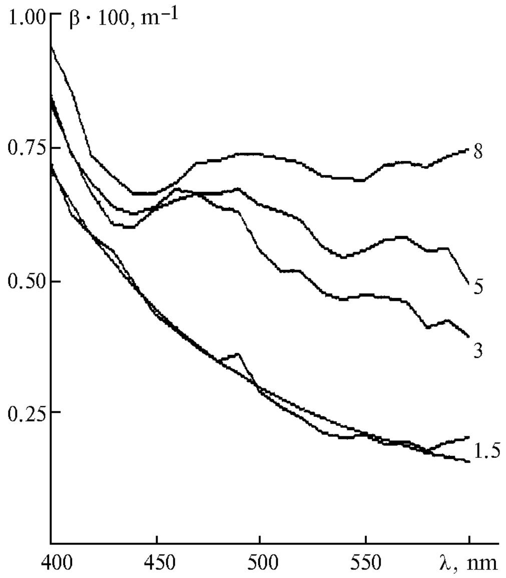

Fig. 3. Spectra of the backscattering coefficient calculated by Eq. (2). For m = 1.5 the function is given which simulates the Rayleigh molecular scattering by Eq. (4).

One can see that it closely approximates the spectrum of the backscattering coefficient in transparent water.

As the water transparency drops, the scattering by suspended matter is added to the molecular scattering. Usually, in modeling backscattering spectra in eutrophic water, this component is assumed to be proportional to the exponential function of λ with the positive exponent less than 4.3 (Refs. 1 and 12). In this case, backscattering spectra are monotonically decreasing with increasing wavelength in water of any type. However, as is seen from the figure, at large m the backscattering coefficient even increases at $\lambda > 450$ nm.

To explain this anomalous behavior, let us consider in a more detail the process of light backscattering on the natural suspended matter in water with high phytoplankton concentration.

Light scattering in water with high phytoplankton concentration

Consider the process of light backscattering on a large particle of the natural suspended matter taking into account the fact that this suspended matter contains colored fragments, such as phytoplankton pigments and detritus, and a particle surface can adsorb colored substances from the solution. Then, in the two-flux approximation

$$F_{\uparrow} = F_{\downarrow}\, a \exp\{-2\delta[\kappa'_{ys500}\exp[-g(\lambda-\lambda_0)] + \kappa'_p(\lambda) + \kappa'_{sm}]\}, \tag{5}$$

where $F_{\uparrow}$ and $F_{\downarrow}$ are the upwelling and downwelling radiation fluxes at a particle in the ocean; a is the albedo of a white particle; δ is the effective path the light traverses in a semitransparent particle; κ'_{ys500} is the absorption coefficient of the yellow substance in detritus at $\lambda = 500$ nm; g is the exponent coinciding with the experimentally obtained exponent for the yellow substance in the solution, $g = 0.015\ \text{nm}^{-1}$ (Ref. 11); $\kappa'_p(\lambda)$ is the absorption coefficient of phytoplankton pigments contained in a particle, κ'_{sm} is the absorption coefficient of the particle itself.

According to Eq. (5), the albedo of the colored particle differs from that of the white particle by the presence of exponent. The backscattering coefficient of the coarse fraction of suspended matter has the form

$$\beta_c =$$
$$= S^* N a\{1 - 2\delta[\kappa'_{ys500}\exp[-g(\lambda-\lambda_0)] + \kappa'_p(\lambda) + \kappa'_{sm}]\}.$$

Here S^* is the effective area of a particle; N is the number of particles in a unit volume. In this equation, the exponent is presented as a power series, what is possible because of the small size of particles.

Thus, the backscattering coefficient in water with high concentration of phytoplankton and products of its vital activity can be simulated by the function of the following form:

$$\beta = \beta_{w500}(\lambda_0/\lambda)^{4.3} + \beta_{f500}(\lambda_0/\lambda)^{4.3} +$$
$$+ \beta_c\{1 - \chi\exp[-g(\lambda-\lambda_0)] - \varphi\kappa^*_p(\lambda)\}. \tag{6}$$

The first term is for light backscattering by pure sea water (scattering on the Einstein – Smolukhovskii density fluctuations), the second term characterizes backscattering from the fine fraction of the suspended matter (it is assumed that the scattering by the fine fraction with particle size much less than the radiation wavelength has the spectral dependence similar to the spectrum of molecular scattering), and the third term characterizes backscattering from the coarse fraction. Here β_c is the non-selective backscattering coefficient proportional to the total concentration of the coarse fraction in the sea water; χ is the parameter proportional to the concentration of the yellow substance in particles; $\kappa^*_p(\lambda)$ is the function having the form of the specific absorption spectrum of phytoplankton pigments; φ is the parameter proportional to the pigment concentration in the suspended matter.

In the general case, the scattering coefficient is the function of four unknown parameters: β_{f500}, β_c, χ, φ. To reveal the general regularities in the backscattering spectrum for water with high productivity at large m, we fitted the model function to the empirical backscattering spectra in the region of 450–600 nm with two fitting parameters β_c and χ. Actually, in this spectral region the influence of the fine fraction of the suspended matter and light absorption by phytoplankton fragments are far less significant than two other factors: nonselective scattering and absorption by the yellow substance.

Figure 4 shows the empirical spectra of backscattering at suspended particles. For water with $m = 8$ (chlorophyll concentration of about 2.3 mg/m^3, Ref. 12) the model function is given with the parameters obtained from fitting by the least-square method:

$$\beta_{mod} = \beta_c\{1 - \chi\exp[-g(\lambda-\lambda_0)]\}. \tag{7}$$

Fitting gave the following values of the parameters: $\beta_c = 0.0064$ and $\chi = 0.34$. It is seen that the proposed function closely approximates the light backscattering process in the eutrophic water of open type.

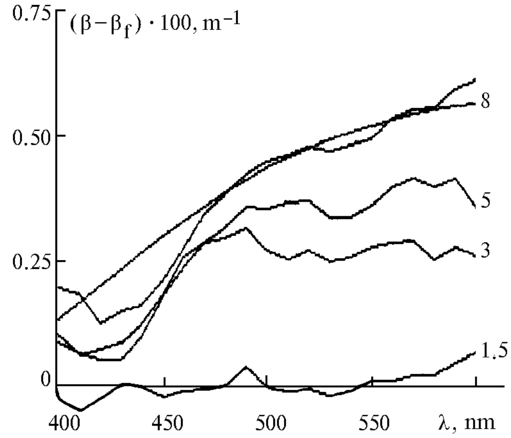

Fig. 4. Spectra of the coefficient of backscattering on suspended particles. The spectra were obtained by subtracting the Rayleigh backscattering spectrum of pure seawater from the spectra for $m = 1.5$, 3.0, 5.0, and 8.0. For $m = 8$ the model function described by Eq. (7) is shown.

Similar calculations were made for other values of $m > 3$. As would be expected, the coefficient of nonselective scattering by particles proved to be proportional to the nonselective absorption coefficient with the proportion coefficient $\beta_c \sim 0.1\ \kappa_{sm}$, and the parameter χ well correlates with the concentration of the dissolved yellow substance in the seawater with the coefficient ~ 20. These relations can be used for simulating the backscattering process in the open ocean, but they call for additional check before being applied to coastal waters. However, the form of the function simulating the backscattering spectrum is the same for both the open-ocean and coastal waters.

Thus, based on analysis of the experimental data, it is shown that as the concentration of natural suspended matter increases, the spectral behavior of its backscattering coefficient becomes anomalous: the backscattering coefficient in the shortwave (blue) spectral region proves to be less than in the longwave region. This allows us to assume that the yellow substance contained in detritus and adsorbed on the surface of mineral particles has a significant effect on the light scattering by particles. In this case, the albedo of a large particle in the shortwave spectral region decreases, what explains the anomalous behavior of the backscattering coefficient. This effect becomes pronounced at the water type index *m* higher than three, that is, at phytoplankton pigment concentration higher than 0.5 mg/m^3. The use of the proposed mechanism of scattering when modeling processes of formation of the spectrum of radiation upwelling from the sea surface allows the higher accuracy to be achieved in solving inverse problems of determination of concentrations of natural admixtures in the seawater.

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