Parameterization of light scattering for solving the inverse problem of determining the concentrations of the principal light scattering and absorbing admixtures in shelf waters*

OCEANOLOGIA, 43 (4), 2001.
pp. 479–485.

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KEYWORDS
Light absorption
Backscattering
Bio-optical modelling

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Manuscript received 16 November 2001, reviewed 20 November 2001, accepted 25 November 2001.

Abstract

A method for estimating the water backscattering coefficient was put forward on the basis of experimental data of diffuse attenuation coefficient for downwelling irradiance and irradiance reflectance. Calculations were carried out for open sea waters of different types and the spectral dependencies were found ('anomalous' spectra) and explained. On this basis, a new model of light backscattering on particles in the sea is proposed. This model may be useful for modelling remote sensing reflectance spectra in order to solve the inverse problems of estimating the concentration of natural admixtures in shelf waters.

1. Introduction

It is well known that to solve the inverse problem of water content from remote sensing data in shelf areas it is necessary to parameterize both water absorption and water scattering. To model absorption, one needs to know the absorption spectra of pure water and chlorophyll, and also the exponential yellow substance spectrum (Jerlov 1976, Morel & Prieur 1977,

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* This paper was presented at the 'Third Workshop on Luminescence and Photosynthesis of Marine Phytoplankton', Sopot-Sulęczyno, 8–12 October 2001.

Prieur & Sathendranath 1981, Baker & Smith 1982, Monin 1983, Morel 1988). Sea water absorption is often modelled with two unknown parameters – the chlorophyll pigment concentration and the yellow substance absorption coefficient. We insist on adding a third parameter – the absorption coefficient of suspended matter – as we have estimated that it is of great importance in open ocean waters (Pelevin & Rostovtseva 1997). The backscattering spectrum has been less throroughly studied, since it is quite difficult to separate backscattering from absorption. Some interesting results were obtained by Woźniak et al. (1995). We suggest using the numerous data of contact measurements obtained during the cruises of IO RAN ships all over the World Ocean to calculate the relevant spectra in ocean waters of different types. Light backscattering can be modelled on the basis of these data.

2. Method of assessing light backscattering spectra

Two basic characteristics of the solar light field in the upper layer of ocean were chosen: the diffuse attenuation coefficient for downwelling irradiance K_d and the irradiance reflectance R, which are connected by the formula

$$R = k\, b_b/(a + b_b) \cong k\, b_b/K_d, \tag{1}$$

where b_b is the backscatter coefficient, a is the absorption coefficient, k is an empirical non-selective coefficient taking values from 0.25 to 0.31. Thus, having measured the spectra of K_d and R we obtain

$$b_{b,\lambda} \cong K_{d,\lambda}\, R_\lambda\, /k. \tag{2}$$

3. Application of the method to the whole range of open ocean waters

The backscatter coefficient spectra can be calculated for all types of open ocean waters by means of the optical index m (Pelevin 1985). In Fig. 1 the spectral dependence is given for the downward irradiance attenuation coefficient and the diffuse irradiance reflection coefficient in oligotrophic ($m = 1.5$), mesotrophic ($m = 3$ and 5) and eutrophic ($m = 8$) waters.

The spectra of the backscatter coefficient calculated for the same water types are given in Fig. 2. To confirm the validity of this method, we compared the spectrum for practically pure water ($m = 1.5$) with the well-known spectrum of molecular scattering

$$b_{b\,\mathrm{mol}} = b_{b,\lambda_0}(\lambda_0/\lambda)^{4{,}3}. \tag{3}$$

One can see these spectra practically coincide.

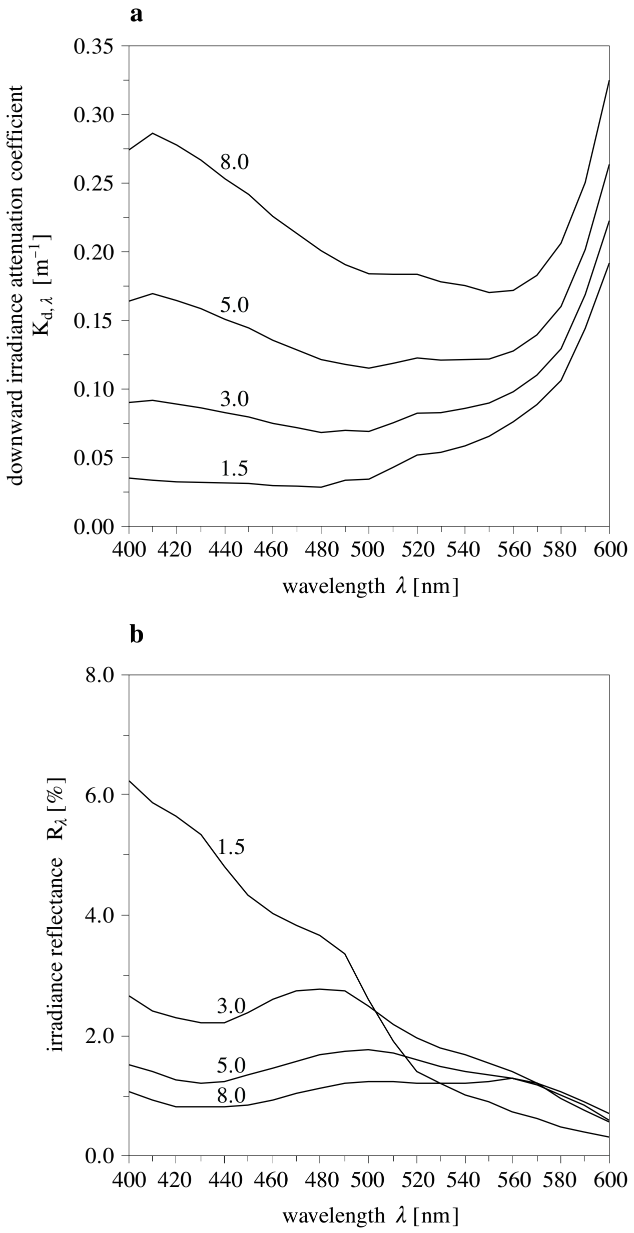

Fig. 1. Spectra of the averaged downward irradiance attenuation coefficient K_d (a) and irradiance reflectance R (b) measured in oligotrophic ($m = 1.5$), mesotrophic ($m = 3$ and 5) and eutrophic ($m = 8$) waters

By subtracting the backscattering of pure water from the spectra obtained, we calculated the backscatter coefficient of suspended particles (Fig. 3).

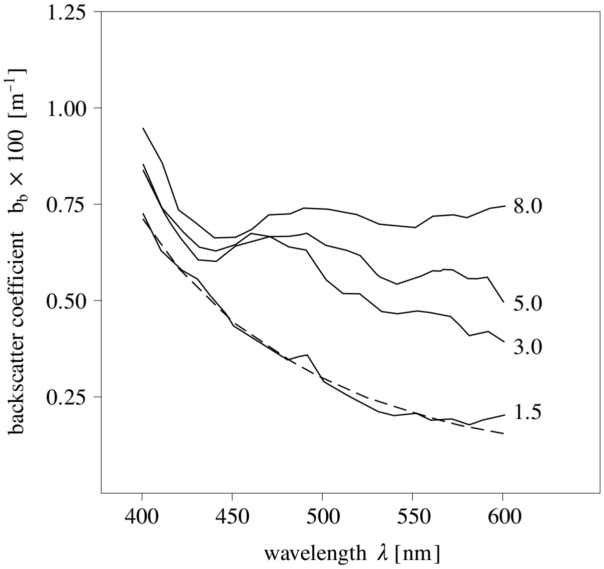

Fig. 2. Spectra of the backscatter coefficient calculated from contact measurement data for various types of ocean waters characterized by the water type optical index m. The spectrum for oligotrophic waters ($m = 1.5$) is compared to the well-known molecular backscattering spectrum

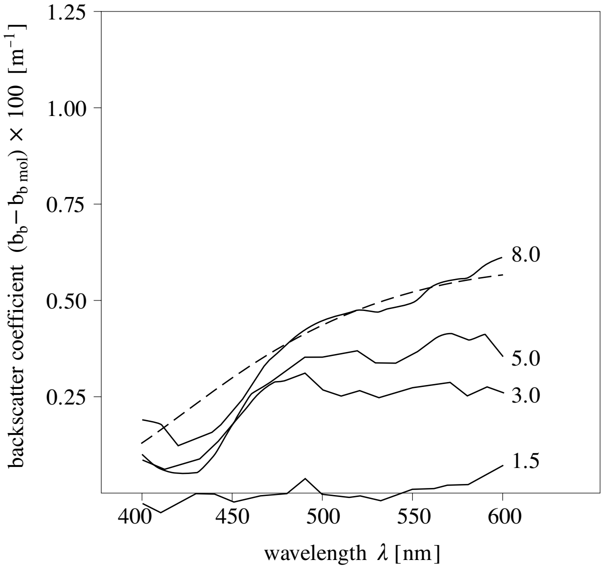

Fig. 3. Spectra of the backscatter coefficient for suspended matter calculated from contact measurement data for various types of ocean waters. The calculated model spectrum is given for some eutrophic waters ($m = 8$)

As the water transparency decreases (i.e. when m increases), scattering on suspended matter particles becomes more important. For modelling their contribution, power functions with different positive indices are usually chosen (Woźniak et al. 1995). But in this particular case, the backscattering spectra would decrease monotonically with λ. Nevertheless, our calculations show this to be untrue for productive waters.

4. Explanation of the 'anomalous' backscattering spectrum

To make this 'anomalous' phenomenon clear, we will consider the process of light backscattering on a rather large particle of suspended matter. We shall take into account the fact that it contains coloured fragments such as phytoplankton pigments and detritus, The particles may also have adsorbed some coloured substances from the solution. Then in double stream approaching the upward light flux $F_{\uparrow}$ is given by

$$F_{\uparrow} = F_{\downarrow}\, A \exp\{-2\delta\,[a_{ys,\,500} \exp[-g(\lambda-\lambda_0)] + a_p(\lambda)]\}. \tag{4}$$

where $F_{\downarrow}$ is the downward light flux, A is the grey particle albedo, δ is the effective depth of light penetration into the particle, $a_{ys,\,500}$, $a_p(\lambda)$ are the absorption coefficients of yellow substance in detritus and chlorophyll pigments in the particle. Thus, the albedo of a coloured particle differs from that of a grey particle by an exponential multiplier which can be decomposed in a series because of the small sizes of the particles.

The backscatter coefficient of suspended matter in sea waters can be modelled by the following function:

$$b_{b,\,sm} = b_{b,\,S}(\lambda_0/\lambda)^{4,3} + b_{b,\,L}\,(1-\chi \exp[-g(\lambda-\lambda_0)] - \varphi\, a_p(\lambda)), \tag{5}$$

where $b_{b,\,S}$ is the small particles backscattering coefficient (presumably, the scattering on particles with dimensions less than the relevant light wavelengths is analogous to molecular scattering), $b_{b,\,L}$ is a coefficient of backscattering by large particles, χ and φ characterize the participation of yellow substance in the particles and chlorophyll pigments in the scattering process.

5. Modelling of backscattering for the solution of inverse problems

If we consider scattering in the spectral band 450–600 nm, the number of parameters can be reduced, as the spectral dependencies of yellow substance and chlorophyll are quite similar here, and for backscattering by large particles only two parameters are necessary:

$$b_{b,\,L}(1-\chi \exp[-g(\lambda-\lambda_0)] - \varphi\, a_p(\lambda)) \Rightarrow b_{b,\,L}\,(1-\chi' \exp[-g(\lambda-\lambda_0)]). \tag{6}$$

Applying this formula to the backscattering spectra of open ocean waters (Fig. 3) we calculated the values of these parameters.

It turns out that for productive waters with $m > 3$ ($C_p > 0.5$ mg m^{-3} the scattering on small particles is negligible ($b_{b,S} = 0$), $b_{b,L}$ correlates to the suspended matter absorption coefficient, and the coefficient characterizing the 'colour of the particles' takes practically the same value ($\chi' \cong 0.14$) for the whole range of ocean waters.

The suggested model function is useful for solving inverse problems in shelf waters (case 2 waters). It was applied to modelling the remote sensing reflectance spectra measured in the Ionian and Black Seas. The results are given in Fig. 4.

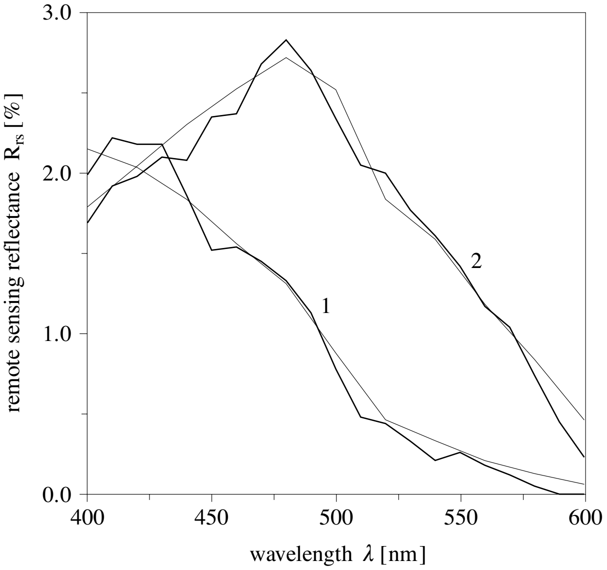

Fig. 4. Modelling the spectra of remote sensing reflectances measured in the Ionian (1) and Black (2) Seas using the new formula for backscattering
$b_{b\,sm} = b_{b,S}(\lambda_0/\lambda)^{4,3} + b_{b,L}(1 - \chi' \exp[-g(\lambda - \lambda_0)])$
$1 - b_{b,S} = b_{b,L} = 0;\ a_{py} = 0.0025;\ a_{sm} = 0.004$
$2 - b_{b,S} = 0.0015;\ b_{b,L} = 0.005;\ a_{py} = 0.017;\ a_{sm} = 0.005$

6. Conclusions

On the basis of a large amount of experimental data obtained during the cruises of the research ships of the Shirshov Institute of Oceanology, the light backscattering coefficient spectra were calculated for ocean waters of different types. The 'anomalous' spectra for productive waters were found and explained. After that, a new model for the suspended matter backscattering coefficient spectrum was developed. This model is useful for modelling remote sensing reflectance spectra in order to solve the inverse problems of estimating concentration in shelf waters. This method was applied to Ionian and Black Sea waters.

References

Baker K. S., Smith R. C., 1982, *Bio-optical classification and model of natural waters 2*, Limnol. Oceanogr., 27 (3), 500–509.

Jerlov N. G., 1976, *Marine optics*, Elsevier, Amsterdam–New York, 231 pp.

Monin A. S. (ed.), 1983, *Oceanic optics. Vol. 1. Physical optics of the ocean*, Nauka, Moscow, 372 pp., (in Russian).

Morel A., 1988, *Optical modelling of the upper ocean in relation to its biogenous matter content (case 1 waters)*, J. Geophys. Res., 93 (C9), 10749–768.

Morel A., Prieur L., 1977, *Analysis of variations in ocean color*, Limnol. Oceanogr., 22 (4), 709–722.

Pelevin V. N., 1985, *Optical phenomena on the ocean surface*, [in:] *Phenomena on the ocean surface*, A.Ṡ. Monin & V. P. Krasitskii (eds.), Gidrometeoizdat, Leningrad, 318–329, (in Russian).

Pelevin V. N., Rostovtseva V. V., 1997, *Estimation of lightscattering and lightabsorbing admixture concentration in open ocean waters of different types*, Atm. Oceanic Opt., 10 (9), 989–995.

Prieur L., Sathiendranath S., 1981, *An optical classification of coastial and oceanic waters based on the specific spectral absorption curves of phytoplankton pigments, dissolved organic matter and other particulate materials*, Limnol. Oceanogr., 26 (4), 671–689.

Woźniak B., Smekot-Wensierski W., Darecki M., 1995, *Semi-empirical modelling of backscattering and light reflection coefficients in WC1 seas*, Stud. i Mater. Oceanol., 68, 61–90.