ESTIMATING THE CONCENTRATION OF LIGHT SCATTERING AND ABSORBING SUBSTANCES IN THE OCEAN WATERS OF DIFFERENT TYPES

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Estimations of the concentration of basic light scattering and absorbing components of the sea water, including chlorophyll are obtained. A Table is composed of the estimates of concentrations for practically all types of sea waters, that can be found in the open ocean. That makes it possible to determine the contents of the basic ecological components in the open ocean by the only parameter m, calculated from the value of extinction coefficient of water along vertical direction. Using a map of water types, the data of direct shipborne measurements or estimations of m from the data of measurements of other parameters, it is possible to estimate the composition of the top layer of the ocean waters practically in any area of World Ocean using this Table. Besides, if measurements of the light extinction along vertical direction at different depths are available, the method developed enables one to estimate the depth distribution of the basic ecological components of waters of the open ocean.

The estimation of the content of chlorophyll and other light absorbing and scattering impurities of the sea water (let us for brevity call them the basic ecological components) in various areas of the World Ocean is one of the urgent problems when solving various ecological and applied problems (estimation of bioefficiency of the World Ocean, distribution of fish resources, ecological monitoring and others).[1–3] The widely used[4–5] empirical techniques for determining the chlorophyll concentration from a color index do not provide high accuracy. In 1995 we have proposed a technique[6] for estimating the chlorophyll, dissolved organic "yellow" substance (DOS) and light absorbing "grey" suspension concentrations by optimizing the model of a light absorption spectrum of sea water, with latter being estimated from measurements of the extinction coefficient of water along vertical direction and diffuse reflection of light by sea.

In this paper we analyze the spectra of absorption and scattering of light by sea using the technique from Ref. 6, and calculate the composition of sea water practically for all types of the ocean waters. The data obtained can be used for estimation of the distribution of the basic ecological components in any area of the open ocean.

1. SPECTRA OF LIGHT ABSORPTION BY WATERS IN OPEN OCEAN

As known, the concentrations of the basic light absorbing and scattering impurities in the open ocean can differ in various areas by tens and even hundred times, however, the ratios between them change in a much narrower limits, because these impurities are the products of life activity (biological cycle) of the sea plankton.[1,8] This circumstance allows the construction of a one-parameter classification of all waters outside of shelf by the parameter

$$m = 100 \log e\, \alpha_{500},$$

where α_{500} is the extinction coefficient of water along vertical direction at $\lambda = 500$ nm. Such a classification of waters of the open ocean was proposed in Refs. 7 and 8. It was shown, that for waters with identical m value both the spectra of light absorption along vertical direction, and the spectra of the diffuse reflection of light by sea are a little bit different. As follows from the analysis of more than 350 spectra of the light extinction in different areas of the World Ocean, typical dependences were received for a range of possible m values from 1.2 in the Sargasso Sea up to 9–11 in Peruvian and Atlantic upwellings (Table I) and the estimate of their rms errors[8] is given. Spectra of the sea diffuse reflectivity[8] were similarly processed.

These data make up the array of initial data for obtaining absorption spectra of sea water. A relationship between the spatial density of absorption in an elementary volume and the vector of radiative energy transfer **H** is used:

$$\varkappa E^0 = -\operatorname{div} \mathbf{H}, \quad (1)$$

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where $\varkappa$ is the absorption coefficient of water; E^0 is the spatial illumination of a given volume ($E^0 = \int_{4\pi} B \, d\omega$, B is the brightness of radiation). Since the horizontal gradients of optical properties of water are much less than the vertical ones (plane layer medium) and the scale of the surface illumination inhomogeneity significantly exceeds the scale of the vertical variability of the light field in water, the horizontal gradients of **H** can be neglected. The vertical component of the vector **H** is equal to the difference of illuminations of an elementary volume from the above ($E_\downarrow$) and from below ($E_\uparrow$). Then Eq. (1) takes the form

$$\frac{\partial \, (E_\downarrow - E_\uparrow)}{\partial z} = - \varkappa \, E^0. \qquad (2)$$

TABLE I. Extinction coefficient of sea water along vertical direction, m^{-1}.

λ,	m											
nm	1.2	1.5	2	3	4	5	6	7	8	9	10	11
380	0.026	0.040	0.059	0.110	0.142	0.185	0.231	0.276	0.316	0.356	0.404	0.449
390	0.025	0.038	0.056	0.104	0.135	0.176	0.221	0.264	0.302	0.342	0.389	0.433
400	0.024	0.036	0.054	0.100	0.130	0.170	0.214	0.255	0.292	0.332	0.379	0.423
410	0.022	0.033	0.052	0.095	0.125	0.164	0.207	0.247	0.284	0.323	0.370	0.414
420	0.021	0.032	0.051	0.092	0.122	0.160	0.202	0.241	0.277	0.316	0.363	0.408
430	0.021	0.032	0.050	0.089	0.119	0.156	0.197	0.235	0.270	0.309	0.355	0.400
440	0.021	0.032	0.049	0.087	0.115	0.151	0.191	0.228	0.262	0.299	0.345	0.388
450	0.021	0.031	0.048	0.083	0.111	0.145	0.183	0.219	0.251	0.287	0.331	0.373
460	0.021	0.031	0.046	0.080	0.106	0.138	0.174	0.208	0.238	0.273	0.314	0.353
470	0.021	0.030	0.044	0.075	0.100	0.131	0.164	0.195	0.223	0.256	0.294	0.330
480	0.021	0.029	0.042	0.071	0.094	0.122	0.152	0.181	0.207	0.237	0.272	0.305
490	0.025	0.033	0.045	0.071	0.093	0.119	0.146	0.172	0.196	0.224	0.255	0.285
500	0.028	0.034	0.046	0.069	0.092	0.115	0.138	0.161	0.184	0.207	0.230	0.253
510	0.036	0.042	0.051	0.073	0.093	0.114	0.137	0.159	0.179	0.201	0.225	0.249
520	0.046	0.052	0.061	0.081	0.099	0.119	0.140	0.160	0.178	0.199	0.221	0.242
530	0.049	0.054	0.062	0.081	0.099	0.117	0.136	0.155	0.172	0.191	0.211	0.231
540	0.054	0.060	0.067	0.085	0.102	0.120	0.138	0.155	0.172	0.190	0.209	0.227
550	0.064	0.070	0.077	0.094	0.111	0.128	0.146	0.163	0.179	0.196	0.214	0.232
560	0.074	0.079	0.086	0.103	0.120	0.137	0.154	0.171	0.187	0.204	0.222	0.239
570	0.089	0.095	0.101	0.118	0.135	0.152	0.170	0.186	0.203	0.220	0.238	0.255
580	0.104	0.109	0.116	0.133	0.150	0.168	0.185	0.202	0.218	0.236	0.254	0.272
590	0.143	0.148	0.154	0.171	0.188	0.206	0.224	0.241	0.257	0.275	0.293	0.311
600	0.189	0.194	0.201	0.217	0.235	0.253	0.270	0.287	0.304	0.322	0.340	0.358

By dividing Eq.(2) by $(E_\downarrow - E_\uparrow) = E_\downarrow(1 - R)$, where R is the factor of diffuse reflection of light by sea, we obtain

$$\alpha \left[1 + \frac{\partial R / \partial z}{\alpha \, (1 - R)} \right] = \varkappa \, \frac{E^0}{E_\downarrow - E_\uparrow} \, . \qquad (3)$$

Here $\alpha = - \frac{1}{E_\downarrow} \frac{\partial E_\downarrow}{\partial z}$ is the extinction coefficient of sea water for the down going radiation. The value R varies weakly as the depth increases. As the experimental data have shown,[1] that second term in the square brackets does not exceed 0.04, that allows one to neglect it. In the right hand side of Eq. (3) there is the expression for the average cosine of the radiation incidence angle:

$$(E_\downarrow - E_\uparrow) / E^0 = \int_{4\pi} B \cos\theta \, d\omega \Big/ \int_{4\pi} B \, d\omega = \mu, \qquad (4)$$

where θ is the angle between the brightness vector and the downwards normal. Then the formula for calculations takes the form[9]:

$$\varkappa = \alpha\mu. \qquad (5)$$

As follows from model experiments and from measurements in Indian Ocean,[10] the average cosine of the incidence angle correlates with the diffuse reflectivity of sea water in accordance with the regression equation

$$\mu = 1 - 0.185 \sqrt{R} \qquad (6)$$

(R is given in percent). The error of determining μ by this formula is $-0.03 < \Delta\mu < 0.04$. Using the average values of R and α obtained in numerous measurements,[8] we obtain the absorption spectra of water of various types (Table II).

TABLE II. Absorption coefficient of the sea water, m^{-1}.

λ,	*m*											
nm	1.2	1.5	2	3	4	5	6	7	8	9	10	11
380	0.014	0.023	0.036	0.074	0.105	0.142	0.183	0.220	0.254	0.290	0.330	0.369
390	0.014	0.022	0.035	0.071	0.100	0.136	0.175	0.210	0.243	0.277	0.318	0.356
400	0.013	0.021	0.034	0.068	0.097	0.131	0.169	0.203	0.235	0.269	0.309	0.347
410	0.012	0.020	0.033	0.066	0.093	0.126	0.163	0.197	0.228	0.262	0.302	0.340
420	0.012	0.019	0.032	0.064	0.091	0.123	0.159	0.192	0.222	0.256	0.296	0.334
430	0.012	0.020	0.032	0.063	0.089	0.120	0.155	0.187	0.216	0.250	0.290	0.327
440	0.013	0.020	0.032	0.061	0.086	0.117	0.150	0.181	0.210	0.242	0.281	0.318
450	0.013	0.020	0.032	0.059	0.083	0.112	0.144	0.174	0.201	0.232	0.269	0.305
460	0.013	0.020	0.031	0.057	0.079	0.107	0.137	0.165	0.190	0.219	0.154	0.288
470	0.013	0.020	0.030	0.054	0.075	0.100	0.128	0.154	0.177	0.205	0.237	0.268
480	0.014	0.019	0.028	0.050	0.070	0.093	0.119	0.142	0.164	0.189	0.218	0.246
490	0.018	0.023	0.031	0.051	0.069	0.091	0.114	0.135	0.155	0.177	0.203	0.228
500	0.020	0.024	0.032	0.050	0.066	0.086	0.106	0.126	0.144	0.164	0.187	0.209
510	0.027	0.031	0.038	0.054	0.070	0.087	0.106	0.123	0.140	0.158	0.178	0.198
520	0.036	0.040	0.046	0.061	0.076	0.092	0.108	0.124	0.140	0.156	0.174	0.192
530	0.039	0.042	0.047	0.061	0.075	0.090	0.106	0.120	0.135	0.150	0.166	0.182
540	0.044	0.047	0.052	0.065	0.078	0.092	0.107	0.121	0.135	0.149	0.164	0.179
550	0.053	0.056	0.061	0.073	0.086	0.100	0.114	0.127	0.141	0.154	0.169	0.183
560	0.062	0.065	0.069	0.081	0.094	0.107	0.121	0.135	0.148	0.161	0.176	0.190
570	0.075	0.079	0.083	0.094	0.107	0.121	0.134	0.148	0.161	0.175	0.189	0.203
580	0.088	0.092	0.096	0.107	0.120	0.134	0.148	0.161	0.174	0.188	0.203	0.217
590	0.122	0.125	0.129	0.141	0.154	0.167	0.181	0.195	0.208	0.222	0.237	0.252
600	0.163	0.166	0.170	0.181	0.194	0.208	0.222	0.236	0.249	0.263	0.278	0.293

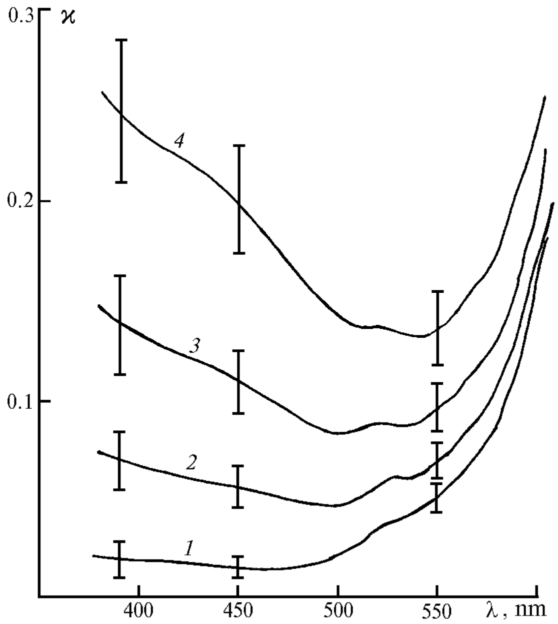

FIG. 1. Absorption spectra of water of different types: 1) $m = 1.5$ *(oligotrophic water); 2) and 3)* $m = 3$ *and* $m = 5$, *respectively (mesotrophic water); 4)* $m = 8$ *(eutotrophic water).*

The absorption spectra of four types of water are shown in Fig. 1 as an example. There is a well seen evolution of the spectra with absorption minimum moving toward yellow region, that is caused by an increase of the chlorophyll and DOS concentrations.

Thus these data characterize the light absorption by sea waters of a different types. The distribution of the index of water types *m* in the World Ocean can be found in Ref. 13.

2. CONTENT OF BASIC LIGHT ABSORBING AND SCATTERING COMPONENTS IN WATER AREAS WITH DIFFERENT INDICES OF WATER TYPES

The statistically averaged absorption spectra obtained allow one to calculate most probable concentrations of the basic light absorbing and scattering components practically in any area of the open ocean. The following expression is used as a model for the absorption

$$\tilde{\varkappa}_\lambda = \varkappa_{w,\lambda} + C_p\, \varkappa^*_{p,\lambda}(C_p) + \varkappa_{ys} \exp\{-g(\lambda - \lambda_0)\} + \varkappa_{sm}, \quad (7)$$

where $\varkappa_{w,\lambda}$ is the absorption of light by pure water; C_p is the chlorophyll concentration in mg/m^3; $\varkappa^*_{p,\lambda}$ is the specific absorption of light by phytoplankton pigments, which depends on the chlorophyll concentration; $\varkappa_{ys}$ is the absorption coefficient of the "yellow" substance at the wavelength $\lambda_0 = 500$ nm; g is the power index, obtained experimentally,[14] $g = 0.015$ nm^{-1}; $\varkappa_{sm}$ is the absorption coefficient by suspended particles without phytoplankton pigments.

To find the impurity concentrations in a water area with a particular value of the water type index *m* let us search for a minimum of the criterion function

$$P_\Sigma = \sum_{i=1}^{N} (\varkappa_{\lambda i}(m) - \tilde{\varkappa}_{\lambda i})^2 \qquad (8)$$

in the 3D space of parameters $x = C_p$, $y = \varkappa_{ys}$, $z = \varkappa_{sm}$. Here $\varkappa_{\lambda i}(m)$ are the values taken from Table II; $\tilde{\varkappa}_{\lambda i}$ are the model (7) values. Actually this means a selection of such values of the impurity concentration, which will provide the least deviation from the values, obtained on the basis of statistically averaged experimental data. The technique of minimization is described in detail in Ref. 6.

For the absorption coefficient of pure sea water, we took its value at minimum optical index observed in World Ocean m, equal to 1.15, (this extremely small value was measured in the region of anticyclonic circulation and downwelling in the Caribbean sea[11]). The spectral values of the absorption coefficient for $m = 1.15$ were obtained by linear extrapolation (Table III). The dependence of the specific absorption of phytoplankton on the concentration was taken according to Refs. 12 and 15. The calculations were carried out in the wavelength range from 380 to 600 nm. The results of calculations are shown in Table IV, and are plotted in Fig. 2.

The values of C_p measured in Atlantic Ocean at numerous stations and averaged for each m are also shown in Fig. 2 for a comparison of the results obtained from direct measurements of the chlorophyll pigment concentration. It is seen that the results of calculation and direct measurements well agree. The graphical presentation of the results of calculation enables one to reveal an interesting feature: almost proportional increase of the chlorophyll concentration and products of its destruction (DOS) is observed up to the value $m \sim 7$–8 at the transition from less productive waters to the more productive ones. It is the area of an equilibrium condition. For the waters characterized by large m value, the proportions are sharply broke: the chlorophyll concentration increases much faster, than the DOS concentration that corresponds to the upwelling zones.

Let us determine the error of the obtained estimates. The rms error of α varies from several percents for the central part of the spectrum up to ~10% on the border of the selected wavelength range.[8] The values R used for the calculation have an error ~10%. However the value R enters in Eq. (6) under a root sign and with a factor less than 0.2. Taking into account this fact and averaging the result over the whole range, it is possible to show, that the estimate of the absorption coefficient for the given m has an error ~10 %. It was shown in Ref. 6, that the error in estimating the concentration of the basic ecological components of sea water makes no more than 20–25% at the variations of the parameters entering in Eq. (7) in the limits of their possible variations and the variations of the value of the absorption coefficient with a factor no more than 10%.

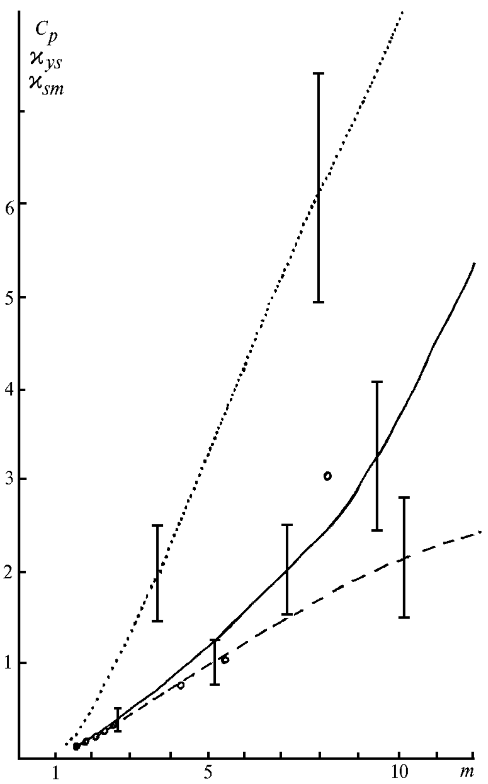

FIG. 2. Dependence of concentrations of basic light scattering and absorbing components on the type of sea water: —— *– chlorophyll concentration* C_p, mg/m^3; – – – *–absorption coefficient of dissolved organic substance* $\varkappa_{ys}\cdot 10^2$, m^{-1}; • • • • *– absorption coefficient of the suspension without taking into account the chlorophyll pigments* $\varkappa_{sm}\cdot 10^2$, m^{-1}; ○ *results of direct measurements of the chlorophyll concentration.*

TABLE III. Absorption coefficient of pure sea water, m^{-1}.

λ	$\varkappa_w$	λ	$\varkappa_w$	λ	$\varkappa_w$	λ	$\varkappa_w$
380	0.013	440	0.011	500	0.019	560	0.061
390	0.012	450	0.012	510	0.026	570	0.075
400	0.012	460	0.012	520	0.035	580	0.088
410	0.011	470	0.012	530	0.038	590	0.121
420	0.011	480	0.013	540	0.043	600	0.162
430	0.011	490	0.017	550	0.052	–	–

TABLE IV. Chlorophyll concentration and absorption coefficients of dissolved organic substance and suspension at λ_0 = 500 nm *depending on the water type index.*

m	C_p, mg/m^3	$\varkappa_{ys}$, m^{-1}	$\varkappa_{sm}$, m^{-1}
1.2	0.002	0.0001	0.00054
1.5	0.019	0.0007	0.0032
2	0.16	0.0014	0.0057
3	0.52	0.0045	0.0135
4	0.81	0.0067	0.023
5	1.16	0.0093	0.033
6	1.6	0.0122	0.042
7	2.0	0.0145	0.052
8	2.3	0.017	0.061
9	2.9	0.019	0.070
10	3.6	0.021	0.079
11	4.3	0.022	0.087

Thus, we have realized the following sequence of operations: averaging of numerous experimental data on the extinction coefficient α of water along vertical direction and of the sea diffuse reflectivity R; classification of the ocean waters on m; calculation of the absorption coefficient $\varkappa$ through the divergence of the transfer vector; optimization of the model of light absorption by sea water. As a result, the estimates are obtained of the concentration of basic light scattering and absorbing components of sea water, including chlorophyll. This allowed us to make the Table of estimates of concentration practically for all types of sea waters, in the open ocean.

Now for the determination of contents of the basic ecological components in open ocean it is sufficient to obtain an estimate only of one parameter m (or α_{500}). Using a map of distribution of the water types (see, for example, Ref. 13) or data of shipborne measurements, or estimates of m from the data of measurements of other parameters (see, for example, Ref. 8), from this Table it is possible to estimate the structure of the top layer of ocean waters practically in any open area of the World Ocean. Besides, if measurements of the extinction coefficient at different depths are available, the developed method will enable one to estimate the in depth distribution of the basic ecological components of waters of the open ocean.

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