Connection between light field parameters and optical properties of seawater

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ABSTRACT

This paper presents results of *in-situ* measurements of optical hyperspectral parameters, chlorophyll concentration and inherent and apparent optical properties of seawater. As a characteristic of hyperspectral optical measurements a CIE dominant wavelength and different color indices are used. Such important optical parameters as downward diffuse attenuation coefficient, diffuse reflection coefficient, beam attenuation coefficient, and seawater euphotic depth are measured and analyzed. Multiple regression relationships that connect hyperspectral data with biological and optical properties are proposed.

Keywords: marine optics, scattering, seawater, optical properties

1. INTRODUCTION

Bio-optical properties of the euphotic sea layer are determined by spectral composition of light upwelling from the ocean. Due to multiple scattering of natural optical radiation an effective path of a photon in seawater is rather large. This insures high sensitivity of upwelling hyperspectral light to the content of dissolved and suspended substances in seawater.

The complete description of spectral properties of radiation ascending from the sea should include a colorimetric analysis of *X-Y-Z* color coordinates of CIE [1, 2]. For qualitative description of seawater color in many cases it is sufficient to have a dominant wavelength λ_D, computed with *X, Y, Z* scheme of CIE relative to the *C*-type light source. Observations of seawater color from the ship or low-flying aircraft detect the light with the same dominant wavelength as the light observed below the sea surface. The light above the sea surface differs from the light below the surface by the presence of white component reflected from the water. This results in the decrease in the color purity of the light ascending from the sea in comparison with the color purity of underwater light. Transparent marine waters have dominant wavelengths in the range of $\lambda_D = 470 \div 473\,\text{nm}$, at the same time the dominant wavelength of turbid yellowish coastal waters reaches the value of 540 nm (Fig. 1).

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2. RELATIONSHIPS BETWEEN BIO-OPTICAL PROPERTIES OF SEAWATER

The Secchi disk or vertical visibility depth z_S is important not only from historical point of view. It can be easily related to such important parameters as diver visibility and diffuse attenuation coefficient [3]. Analysis of *in situ* measured data shows the following regression relationship between vertical visibility depth and dominant wavelength:

$$z_S = \frac{285.7}{\lambda_D - 462.8}, \quad 470 < \lambda_D < 560 \text{ nm}, \quad (N = 121, r = 0.89 \pm 0.02). \tag{1}$$

The dependence (1) is shown in Fig. 2 that contains not only our data, but also results published in Refs. [4, 5].

Let us consider dependence of diffuse attenuation coefficient on the dominant wavelength of water depth. The following regression is obtained from analysis of our data and data taken from Ref. [4]:

$$\overline{\alpha}_{\downarrow}(430) = \left(\frac{0.17634}{\lambda_D}\right)^{2.92}, \quad 470 < \lambda_D < 560 \text{ nm}, \quad (N = 163, r = 0.88 \pm 0.03), \tag{2}$$

Methodical and technical requirements to experimental measurements do not allow to obtain extensive data suitable to produce reliable λ_D for large ocean areas. This lead to the extensive use of the color index proposed by N. Jerlov [6]. By the definition, the color index is the ratio of two ascending radiances measured at two narrow wavelength channels: $J(\lambda_n, \lambda_k) = L_{\uparrow}(\lambda_n) / L_{\uparrow}(\lambda_k)$.

The value of λ_n is often chosen in the range of intensive phytoplankton absorption, and value of λ_k in the range of weak phytoplankton absorption. Consequently, in this particular case, the color index determines relative absorption by chlorophyll and other phytoplankton pigments and it is related to the concentration of these pigments. If $\lambda_n \approx 550$ nm and $\lambda_k \approx 440$ nm, the value of color index. measured in the subsurface layer of the sea, is varied in the range of three orders of magnitude, *i. e.* $0.03 \le J(550, 440) \le 100$.

Our analysis of measurements fulfilled in various regions of world ocean gives the following relationship between chlorophyll concentration and color index:

$$C_{chl} = 0.295 J^{0.74} \quad (J \equiv J(550, 440)). \tag{3}$$

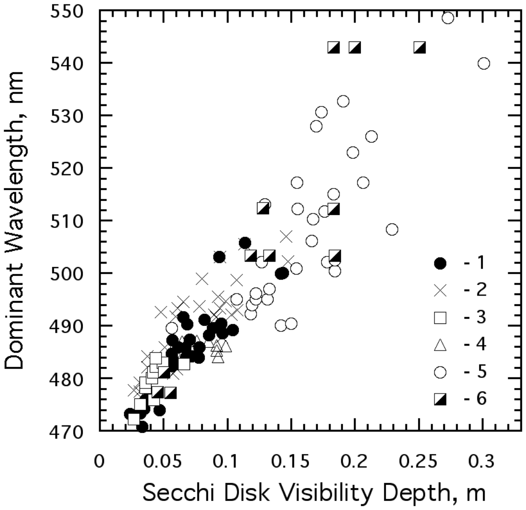

Figure 1. Dependence of seawater color determined by a dominant wavelength of upwelling radiation and vertical visibility depth. Here:
1 - Atlantic ocean (R/V Akademik Vernadsky);
2 - Indian ocean (R/V Akademik Vernadsky);
3 - Mediterranean Sea (R/V Ayudag); 4 – Black sea (Oceanographic platform near Katsiveli, Crimea);
5 - Atlantic Ocean;
6 - Japanese sea, Morel & Prieur [4].

This equation gives the value of chlorophyll concentration C_{chl} (in $\mathrm{mg/m^3}$) averaged over some under-surface sea layer with the depth related to the water transparency.

Experimental measurements did not show any significant difference between color indices determined by ratio of radiances or irradiances. So, we can write:

$$J(\lambda_n,\lambda_k)=\frac{L_\uparrow(\lambda_n)}{L_\uparrow(\lambda_k)}\cong\frac{E_\uparrow(\lambda_n)}{E_\uparrow(\lambda_k)}=q\frac{E_\uparrow(\lambda_n)E_\downarrow(\lambda_k)}{E_\uparrow(\lambda_k)E_\downarrow(\lambda_n)}=q\frac{R(\lambda_n)}{R(\lambda_k)},\quad q=\frac{E_\downarrow(\lambda_n)}{E_\downarrow(\lambda_k)}=\text{const},\tag{4}$$

here $R(\lambda_i)$ is duffuse reflection coefficient at wavelength λ_i, and q is weakly varying value that predominantly depends on atmospheric optical properties. Equation (4) shows that the color index is proportional to the ratio of diffuse reflection coefficients at corresponding wavelengths. If we consider that $R(\lambda)=\text{const}\cdot b_B(\lambda)/a(\lambda)$, here $a(\lambda)$ is an absorption coefficient of seawater, and $b_B(\lambda)$ is a backscattering coefficient, then

$$J(\lambda_n,\lambda_k)=q\frac{b_B(\lambda_n)\,a(\lambda_k)}{b_B(\lambda_k)\,a(\lambda_n)}.\tag{5}$$

Because the color index is determined by conditions of light penetration and backscattering in seawater, its value should be related to the vertical visibility depth that is determined by the same parameters. Our analysis of measurements in waters with the range of Secchi disk visibility between 3 and 44 m gives us the following relationship between color index and vertical visibility:

$$J(540,440)=123/z_S^{2.02}\,,\qquad (N=124,\quad r=0.93).\tag{6}$$

In spite of subjectivness of z_S determination, this value was extensively measured during many decades of oceanological investigations, and its values are broadly available from marine atlases. Equation (6) allows to transfer these historical values to the objective hydro-optical properties and, using Eq. (3) into concentrations of chlorophyll. Further processing with the model of inherent optical properties [8] can produce the whole set of inherent optical properties in the visible range of wavelengths. Color index is connected to the downward diffuse attenuation coefficient according to the following relationship derived by Kozlyaninov and Semenchenko [9]:

$$k_\downarrow=0.068\,J(549,482),\tag{7}$$

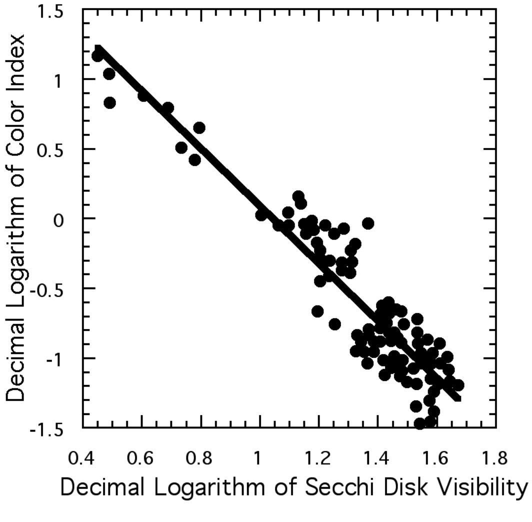

Figure 2. Connection between color index of water column and vertical visibility depth.

which can be used to restore this important parameter either from in-situ measurements of color index or using historical data on z_S and Eq. (6).

By analyzing large massive of published experimental results [10] we obtained the following regressions that couple arbitrary color indices with diffuse attenuation coefficient at 500 nm:

$$k_{\downarrow}(500) = A + BJ(\lambda_n, \lambda_k), \tag{8}$$

$$J(\lambda_n, \lambda_k) = C + Dk_{\downarrow}(500). \tag{9}$$

Coefficients A, B, C, and D to Eqs. (8)-(9) are given in Table 1.

Diffuse reflection coefficient (DRC) $R(\lambda)$ and radiance reflection coefficient (RRC) are two important properties used in ocean optics and optical remote sensing. They are defined by the following equations:

$$R(\lambda) = E_{\uparrow}(\lambda) / E_{\downarrow}(\lambda)\Big|_{z=0}, \qquad \rho(\lambda,\theta,\varphi) = L_{\uparrow}(\lambda,\theta,\varphi) / E_{\downarrow}(\lambda)\Big|_{z=0}, \tag{10}$$

here $E_{\updownarrow}(\lambda)$ denote irradiance, and $L_{\uparrow}$ radiance of light at wavelength λ. The subscript arrow denotes the direction of propagation, z is the depth measured from the sea level. The widely used remote sensing reflectance (RSR) $r(\lambda)$ is nothing but radiance reflection coefficient measured from nadir:

$$r(\lambda) = L_{\uparrow}(\lambda,0,0) / E_{\downarrow}(\lambda)\Big|_{z=0} \equiv \rho(\lambda,0,0). \tag{11}$$

Analysis of RSR spectra, computed from measurements of ascending seawater radiance and descending irradiance, shows significant variability in absolute values and spectral shape of RSR. The increase in the water transparency leads to the shift of the RSR maximum to the blue region. At the same time this maximum looses its distinction and disappears in very clear waters. This behavior of RSR encourage us to investigate connections between the shape of $r(\lambda)$ and bio-optical properties of seawater. Figure 3 displays the experimentally obtained array of values that connect vertical visibility of water z_S with the wavelength of RSR maximum $\lambda_{\max}$. The figure display values obtained in Black, Mediterranean, and Baltic seas as well as in Atlantic Ocean; most values are measured in conditions of cloudless sky. The inset in Fig. 3 shows spectral profiles of RSR that illustrate transformation of spectral shape of remote sensing reflectance with the change in vertical visibility. This connection can be expressed as the following regression:

$$z_S = \exp\left(\frac{593.33 - \lambda_{\max}}{37.04}\right), \quad 475 < \lambda_{\max} < 580\,\text{nm}, \quad \left(N = 89, r = 0.95 \pm 0.02\right). \tag{12}$$

Mean-square spread of experimental values used to obtain Eq. (12) from regression line is ±30%.

The values of beam attenuation coefficient in the range of $420 \div 495$ nm measured during the same set of experiments and averaged over upper 50-m layer give the following regression with the maximum wavelength of RSR:

$$\langle c \rangle_{50m} = \exp\left(\frac{\lambda_{\max} - 521.75}{37.04}\right), \quad 475 < \lambda_{\max} < 580\,\text{nm}, \quad \left(N = 59, r = 0.96 \pm 0.02\right), \tag{13}$$

Mean-square spread of experimental values used to obtain Eq. (13) from regression line is ±25%.

Figure 4 shows relationship between chlorophyll concentration in subsurface water layer measured in Black, Baltic and Mediterranean seas with the wavelength of the RSR maximum. The corresponding regressional relation can be expressed as follows:

Table 1. Values of coefficients in Eqs. (8) and (9).

λ_n / λ_k	C	D	A	B	r^2	λ_n / λ_k	C	D	A	B	r^2
520/440	3.74	5.20	-3.45	1.54	0.90	560/450	4.03	6.86	0.89	1.28	0.94
530/430	2.84	6.1	-1.73	1.34	0.91	560/460	7.40	6.26	0.64	1.37	0.93
530/440	2.91	5.81	-2.16	1.43	0.91	560/470	10.76	5.51	0.16	1.53	0.92
530/450	3.31	4.99	-3.44	1.65	0.91	570/410	-1.52	7.17	1.51	1.23	0.94
530/460	3.55	4.45	-4.16	1.80	0.90	570/420	-0.68	7.64	1.33	1.17	0.84
540/430	2.19	6.67	-1.07	1.28	0.92	570/430	-1.54	7.71	1.39	1.16	0.95
540/440	2.21	6.33	-1.21	1.34	0.92	570/440	-1.63	7.44	1.61	1.18	0.94
540/450	2.63	5.48	-2.26	1.54	0.92	570/450	3.19	6.57	1.07	1.33	0.93
540/460	2.88	4.96	-2.69	1.66	0.91	570/460	6.46	5.98	0.84	1.42	0.92
540/470	3.09	3.41	-3.48	1.86	0.90	570/470	9.58	5.28	0.37	1.59	0.91
550/410	0.70	7.10	1.03	1.18	0.92	580/410	-8.32	6.18	2.27	1.47	0.95
550/420	1.27	7.00	0.27	1.21	0.92	580/420	-6.59	6.34	2.01	1.43	0.95
550/430	1.15	7.16	0.06	1.23	0.93	580/430	-7.07	6.4	2.09	1.42	0.95
550/440	1.04	6.94	0.18	1.26	0.93	580/440	-6.89	6.17	2.30	1.44	0.94
550/450	1.49	6.08	-0.59	1.43	0.93	580/450	-2.98	5.47	1.84	1.61	0.94
550/460	1.49	5.93	-0.43	1.44	0.92	580/460	-0.10	4.98	1.61	1.73	0.93
550/470	2.03	4.85	-1.47	1.71	0.91	580/470	2.76	4.41	1.21	1.93	0.92
560/410	-0.33	7.83	1.70	1.13	0.94	590/410	-0.17	4.10	1.82	2.06	0.92
560/420	-0.05	8.02	1.23	1.12	0.95	590/420	1.66	4.20	1.74	1.96	0.91
560/430	-0.71	8.04	1.25	1.12	0.95	590/430	1.33	4.23	1.76	1.95	0.91
560/440	-0.77	7.77	1.45	1.13	0.94	590/440	1.08	4.10	1.99	1.98	0.90

$$C_{chl} = \exp\left(\frac{\lambda_{\max} - 529.2}{23.585}\right), \quad 475 < \lambda_{\max} < 580\,\text{nm}, \quad (N = 54, r = 0.96 \pm 0.03), \tag{14}$$

Figure 5 shows dependence of diffuse reflection coefficient (DRC) R with downward diffuse attenuation coefficient $k_\downarrow$ at λ = 430 nm. In order to improve statistics of the following equation we also used data obtained in Atlantic Ocean [4]. The corresponding regression is:

$$R(430) = \frac{0.2145}{k_\downarrow(430)^{1.056}}, \quad 0.018 < k_\downarrow(430) < 1.0, \quad (N = 61, r = -0.95 \pm 0.02), \tag{15}$$

here diffuse reflection coefficient R is expressed in % and $k_\downarrow$ in m^{-1}.
coefficient may be expressed in the following simple way:

$$R(430) \approx \frac{0.2}{k_\downarrow(430)}, \tag{16}$$

here R is in %, and $k_\downarrow$ is in m^{-1}. The deviation of values estimated with Eq. (16) from the values shown in Fig. 5 is less than 14% for $k_\downarrow < 0.09\ \text{m}^{-1}$ and less than 6% for $k_\downarrow > 0.2\ \text{m}^{-1}$.

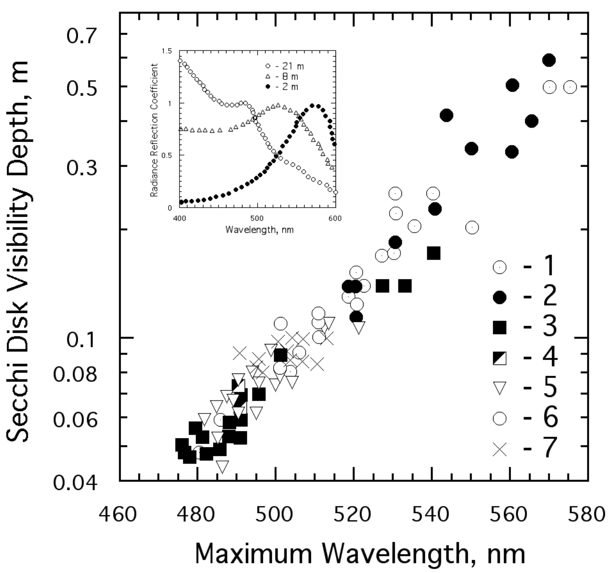

Figure 3. Connection between vertical visibility depth and wavelength of maximum in spectral radiance of water mass $\lambda_{\max}$; here,

1 - Atlantic ocean (R/V Akademik Vernadsky);
2 - Baltic sea (R/V Ayudag);
3 - Black sea (R/V Ayudag);
4 - Mediterranean sea (R/V Professor Kolesnikov);
5 - Black sea (R/V Professor Kolesnikov);
6 - Black sea (Oceanographic Platform, 1980);
7 - Black sea (Oceanographic Platform, 1983).

In the inset: Profiles of the remote sensing coefficients normalized to their maximums for several waters with different z_S.

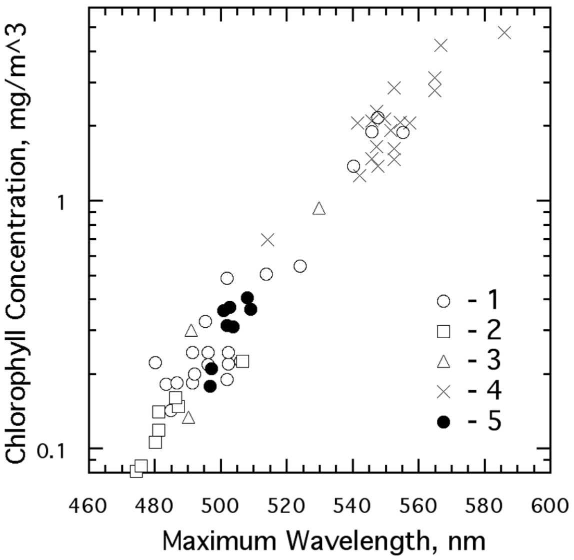

Figure 4. Connection of chlorophyll-a concentration ($\mathrm{mg/m^3}$) for the under-surface sea layer with the wavelength of the maximum of seawater spectral radiance coefficient ρ_w; here,

1 - Black sea (R/V Mikhail Lomonosov, 1984);
2 - Black sea (R/V Mikhail Lomonosov, 1978);
3 - Mediterranean sea (R/V Aytodor);
4 - Baltic sea (R/V Ayudag);
5 - Black sea (Oceanographic Platform).

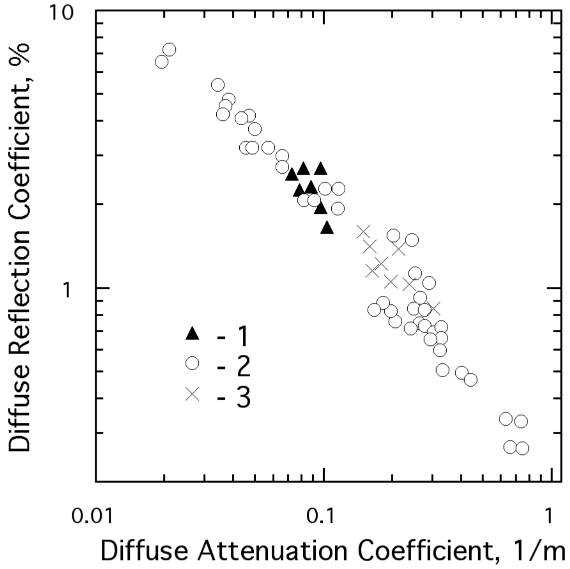

Figure 5. Dependence of Diffuse Reflection Coefficient R of the sea on downward diffuse attenuation coefficient $k_{\downarrow}$ both at $\lambda = 430\,\mathrm{nm}$.

1 - Black sea, (Katsiveli Oceanographic platform);
2 - Atlantic ocean, Morel & Prieur [4];
3 - Atlantic ocean (R/V Mikhail Lomonosov).

In the range of acceptable error the dependence of diffuse reflection coefficient on diffuse attenuation. For many remote sensing and experimental tasks it is important to estimate the depth of the water layer that transforms all directed light into a diffuse light [11]. Because this layer has predominant influence on energetic parameters and spectral structure of ascending light, we should consider variability of bio-optical properties in all this layer. We can accept *a priori* that this depth is equal to the depth when downwelling light attenuates ten times (the depth of 10% of illumination).

According to the definition [12-14], downward diffuse attenuation coefficient is determined by

$$k_{\downarrow} = -\frac{1}{E_{\downarrow}(z)} \frac{dE_{\downarrow}(z)}{dz}, \tag{17}$$

consequently, the downward irradiance at depth z may be expressed as

$$E_{\downarrow}(z) = E_{\downarrow}(0)\exp(-k_{\downarrow}z), \tag{18}$$

The depth when we have only 10% of radiation from above, *i. e.* $E_{\downarrow}(z) = 0.1E_{\downarrow}(0)$ is given by

$$z_{10\%} = -\frac{\ln(0.1)}{k_{\downarrow}} = \frac{2.3}{k_{\downarrow}}. \tag{19}$$

Replacing k with the expression obtained from Eq. (15), we have the following semi-empirical formula:

$$z_{10\%} = 9.89 R^{0.95}\Big|_{\lambda = 430 \text{ nm}}, \tag{20}$$

or, if we use simplified Eq. (16), we obtain:

$$z_{10\%} = 10 R\Big|_{\lambda = 430 \text{ nm}}, \tag{21}$$

here in both Eq. (19) and (20) R is expressed in %, and $z_{10\%}$ is in m. The simplified Eq. (21) gives results that differ from Eq. (20) less than 12% for transparent and less than 3% for turbid waters.

3. RESULTS

We used empirical relationships presented above to estimate ranges of variability of a number of optical parameters for six types of ocean waters that include both open ocean and coastal waters. The waters are divided on five types according to their color. The color is estimated according to the dominant wavelength. The results of these estimations are given in Tab. 2. The ranges of variabilities of bio-optical properties displayed in Tab. 2 reflect results of measurements made in Black and Mediterranean seas and Atlantic Ocean.

Table 2 may be considered as a variant of ocean water classification that differ from other classifications [6, 15-17]. The difference of this classification consists in the fact that major parameters are related to the color of water masses may be determined from remote sensing measurements. The information given in Table 2 is useful for estimation of water optical properties from the board of a ship or low-flying aircraft or helicopter. The use of these data with satellite remote measurements should involve optical atmospheric correction.

Table 2. Bio-optical properties and color of seawater masses.

Water Type → Parameter ↓	Non-productive	Weakly productive	Moderately productive	Average productivity	Productive	Highly productive
Color	violet-blue	blue	blue-green	green	yellow-green	yellow
Color Code	VB	B	BG	G	YG	Y
λ_D, nm	< 470	471-493	494-517	518-542	543-565-	> 566
λ_{eff}, nm [18]	< 465	466-495	486-507	508-515	516-520	> 521
$\lambda_{\max}$, nm	< 495	459-510	511-532	532-546	546-555	> 555
$J(550,440)$	< 0.023	0.025-0.12	1.125-0.75	0.76-1.72	1.73-12.0	> 12.0
$R(430)$,%	> 5.7	5.65-1.26	1.25-0.68	0.67-0.45	0.45-0.34	< 0.34
$\bar{k}_{\downarrow}(430)$, m^{-1}	< 0.046	0.047-.186	0.188-.337	0.340-.495	0.50-0.646	> 0.646
$a(430)$, m^{-1}	< 0.036	0.037-.162	0.163-.294	0.295-0.45	0.451-.585	> 0.59
$(b_B / a)(430)$	> 0.155	0.154-.037	0.036-.02	0.02-.013	0.013-.011	< 0.01
$\bar{c}(420-495)$	< 0.018	0.18-0.73	0.73-1.33	1.33-1.92	1.92-2.45	> 2.45
z_S, m^{-1}	> 38.0	37.5-9.4	9.3-5.2	5.2-3.6	3.6-2.8	< 2.8
$z_{10\%}$, m^{-1}	> 50.1	50.1-12.3	12.3-6.8	6.8-4.6	4.6-3.6	< 3.6
C_{chl}, $\mathrm{mg/m^3}$	< 0.04	0.05-0.45	0.46-1.14	1.15-2.04	2.05-3.00	> 3.00

4. CONCLUSION

The generalization of bio-optical experimental data obtained in different areas of World Ocean presented in this paper gives us a set of useful equation that connect inherent optical properties of seawater with remotely measurable and colorimetric properties of the ocean. A CIE dominant wavelength and different color indices are used as a characteristic of hyperspectral optical measurements. Such important optical parameters as downward diffuse attenuation coefficient, diffuse reflection coefficient, beam attenuation coefficient, and seawater euphotic depth are measured and analyzed. Multiple regression relationships that connect hyperspectral data with biological and optical properties are proposed and discussed.

5. ACKNOWLEDGMENTS

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