Proceedings of the Fourth International Airborne Remote Sensing Conference and Exhibition/21st Canadian Symposium on Remote Sensing,
21-24 June 1999, Ottawa, Ontario, Canada, ISSN 1076-7924, Published by ERIM International, Inc., Ann Arbor, MI, USA

Shipborne measurements of optical and biological properties of Black Sea

Vladimir I. Haltrin,

Naval Research Laboratory, Ocean Sciences Branch, Code 7331, Stennis Space Center, MS 39529-5004, USA
e-mail: <haltrin@nrlssc.navy.mil>

B. A. Nelepo, V. A. Urdenko, E. I. Afonin, V. S. Kotlyarenko, M. E. Lee, O. V. Martynov, L. N. Radaykina, E. B. Shybanov, V. I. Voskresensky,

Marine Hydrophysical Institute, Ukrainian Academy of Sciences, 2 Kapitanskaya St., Sevastopol, 335000, Ukraine

Z. Z. Finenko, and O. A. Yunev

Institute of Biology of Southern Seas, Ukrainian Acad. of Sci., Nakhimov Prospekt, Sevastopol, 335000, Ukraine

ABSTRACT

Results of shipborne measurements of optical and biological properties of the Black Sea are presented. These investigations have been made in 1984 as a part of multilevel experiment that included shipborne and airborne measurements of optical properties of the sea-atmospheric system. Several regression relationships between different optical properties and some optical properties and chlorophyll concentration are presented.

Keywords: Inherent optical properties, biological properties, regression relationship, Black Sea, seawater.

1.0 INTRODUCTION

This work displays and analyzes results of shipborne measurements of optical and biological properties of the Black Sea. These investigations were made in September 1984 as a part of the multilevel experiment that included shipborne and airborne measurements of optical properties of the sea-atmospheric system (See Fig. 1). The shipborne measurements were made from the research vessel 'Mikhail Lomonosov' and the multilevel airborne measurements were made using the laboratory-aircraft AN-30. The measured seawater parameters were: temperature, conductivity, vertical profiles of the beam attenuation coefficient at six visible wavelengths, color index, spectral radiance of downwelling and upwelling light in the spectral range between 380 and 780 nm, vertical profiles of diffuse attenuation and diffuse reflection coefficients at six wavelengths, Secchi disk visibility, concentrations of chlorophyll 'a', phaeophytin 'a', and inorganic phosphorus (Nelepo *et al.*, 1985; Urdenko *et al.*, 1985a, 1985b). The spectral radiance coefficient of the sea have been computed from the measurements of downwelling and upwelling radiances.

The goal of the program was to refine models of the radiative transfer of light in the sea-atmospheric system (Haltrin, 1998a, 1998b, 1999) and to enhance algorithms of retrieving optical and biological properties of the upper photic sea layer. The results of this expedition have been used to improve algorithms of atmospheric correction of optical measurements of sea spectral signatures (Haltrin, 1985). They also have additional value *as in situ* measurements of basic physical and biological properties of the seawater.

Presented to the Fifth International Airborne Remote Sensing Conference and Exhibition,
21-24 June 1999, Ottawa, Canada.

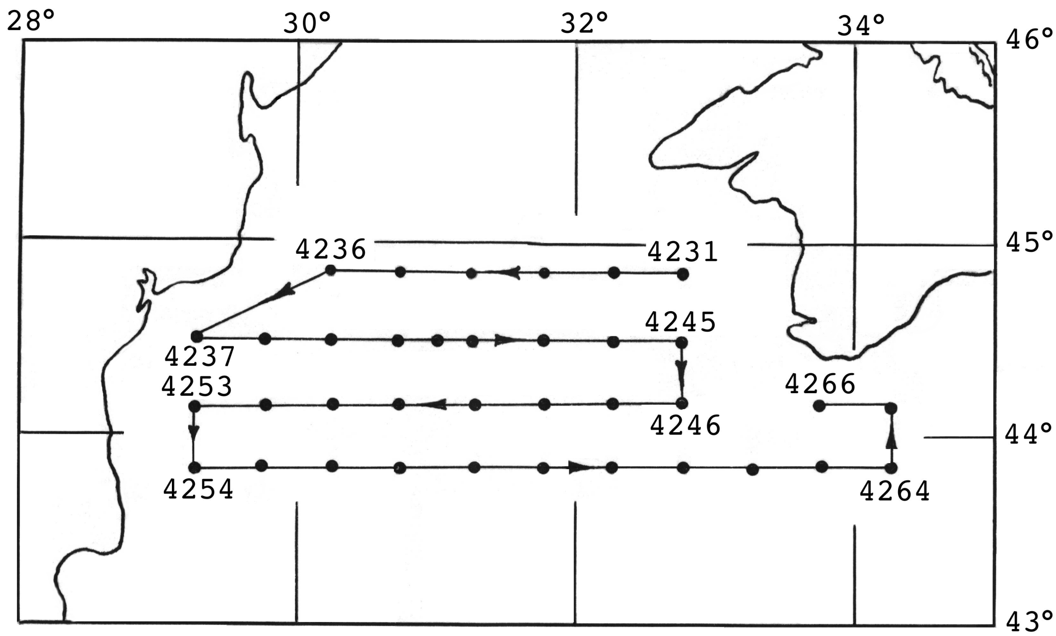

Figure 1. The map of 1984 optical and hydrophysical measurements for the Black Sea.

2.0 HYDROLOGIC MEASUREMENTS

Measurements of hydrologic properties have been accomplished with a probing suite MHI 4102 (ISTOK-5). This suite (Anonymous, 1981) has the following characteristics: temperature measurement range from -2° to +35° C with a mean-square error (MSE) ±0.015%; specific conductivity measurement range from 1.3 to 7.0 cm/m with MSE: ±0.002%; mean-square error of depth measurements was 0.25%; the total time of hydrologic measurements was 0.24 sec.

The tables of temperature, salinity, and relative density profiles measured during this experiment are given in Nelepo (1985).

3.0 OPTICAL PROPERTIES

Measurements of hydrooptical properties were accomplished with the instrumentation developed in the Optics Department of Marine Hydrophysical Institute of Ukrainian Academy of Sciences (UAS):

Vertical profiles of beam attenuation coefficient $c(z)$ (see Fig. 2 and tables in Nelepo, 1985) were measured with a logarithmic photometer-transparency-meter LFP (Neuymin, 1981). The LFP has the following characteristics: spectral center bands: 422, 453, 493, 528, 590, and 625 nm with a dynamic range of $7 \cdot 10^{-2} \le c \le 1.4\,m^{-1}$ with a mean-square error of 3%.

The color index $J(z) = L_u(\lambda_2, z)/L_u(\lambda_1, z)$ (where $L_u(\lambda, z)$ is a nadir directed radiance of upwelling light at depth z, $\lambda_1 = 433\,\mathrm{nm}$, and $\lambda_2 = 564\,\mathrm{nm}$) was measured with a special probe submerged from a vessel's deck to the depths of 1 and 6 m (Neuymin, 1981). Main technical characteristics of this probe are: spectral bands are 443 and 564 nm; viewing angle is 10°; dynamic range of measurements is $0.02 \le J \le 20$ with a mean-square error of 5%.

Spectral density of energetic radiance of downwelling $L_d(\lambda)$ and upwelling $L_u(\lambda)$ light was measured with a scanning telephotometer SPEKTR-1 (Afonin and Lee, 1984) installed on the bow part of the research vessel. The telephotometer SPEKTR-1 has the following characteristics: spectral range is $380 \le \lambda \le 780\,nm$ with a mean-square error of 10%; maximum spectral resolution is 1 nm; range of zenith and azimuth measurement angles is $0° \le \theta, \varphi \le 360°$; viewing angle is 4°; time of the whole spectrum registration is 15 sec; mean-square error of viewing angles settings is ±0.5°; mean-square error of wavelength setting is ±2 nm.

Vertical profiles of downward $k_d(z)$ and upward $k_u(z)$ diffuse attenuation coefficients (Fig. 3) and diffuse reflection coefficient of the sea $R(z)$ were measured with a submersible photometer 3F-6 (Lee and Afonin, 1977). The system has the following characteristics: spectral center wave-

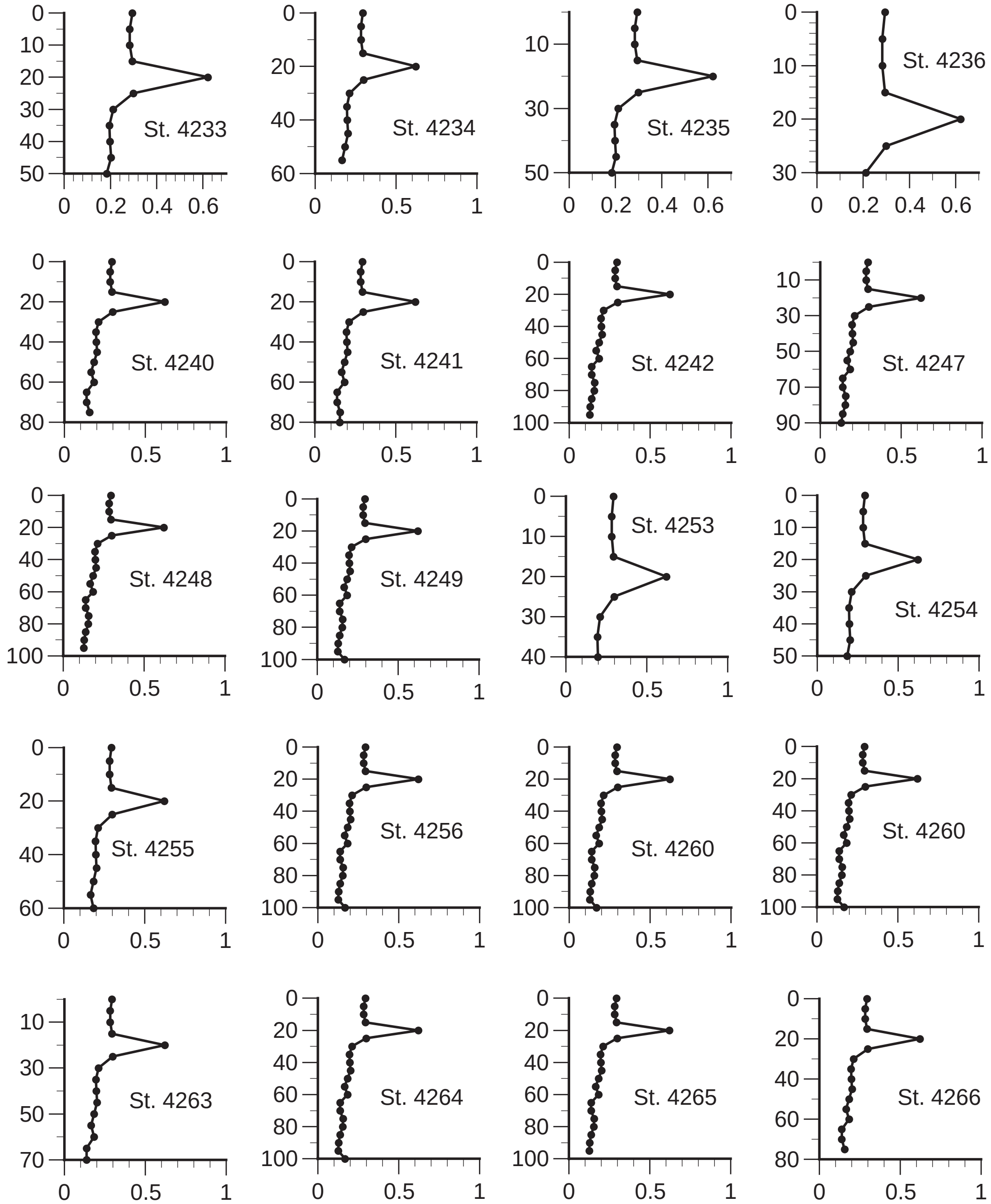

Figure 2. Depth (vertical axis) profiles of beam attenuation coefficient $c(\lambda = 528\,\text{nm}), \text{m}^{-1}$.

lengths are 420, 450, 494, 520, 560, and 600 nm; measurement range for k_d and k_u is $4 \cdot 10^{-3} \le k_d, k_u \le 0.7$ with a mean-square error of 5%; measurement range for R is $0.1 \le R \le 10\%$ with a mean-square error of 6%; the mean-square error of depth measurements is 1%.

Measurements of Secchi disk visibility depth z_s and Forel-Uhle color (see Tab. 1) were made according to a standard procedure (Anonymous, 1977).

Table 1. Secchi disk visibility, water color according to Forel-Uhle scale, and Color Indices

Station No.	z_s, m	Forel-Uhle color	$J(1m)$	$J(6m)$	sea depth, z_B, m	Date	Time
4233	–	–	0.67	1.06	60	08.09.84	08:55
4234	9.5	XIII–XIV	0.94	2.16	70	08.09.84	12:00
4235	9.0	XII–XIII	1.30	2.75	60	08.09.84	16:20
4236	2.5	XII–XIII	3.20	6.70	45	08.09.84	19:15
4240	13.	VI–VII	1.00	1.29	85	09.09.84	10:55
4241	15.	IV	0.75	0.86	125	09.09.84	14:00
4242	14.	V	0.59	0.71	515	09.09.84	17:45
4247	16.	IV–V	0.51	0.55	1500	12.09.84	10:10
4248	17.	V	0.47	0.51	1280	12.09.84	14:15
4249	17.	IV	0.47	0.59	720	12.09.84	18:15
4253	10.	VIII	0.78	1.37	51	13.09.84	08:40
4254	11.	V–VI	0.86	1.20	58	13.09.84	11.30
4255	17.	IV–V	0.67	0.71	68	13.09.84	16:42
4256	–	–	0.49	0.49	150	13.09.84	19:40
4260	17.	IV	0.43	0.47	1820	14.09.84	10:45
4261	17.	V	0.51	0.67	1950	14.09.84	14:45
4264	15.	IV	0.82	0.82	2100	15.09.84	08:30
4265	14.	VI	0.82	1.00	1700	15.09.84	16:00
4265	14.	V	0.94	1.00	1700	16.09.84	11:00
4266	15.	IV–V	0.47	0.51	140	16.09.84	15:00

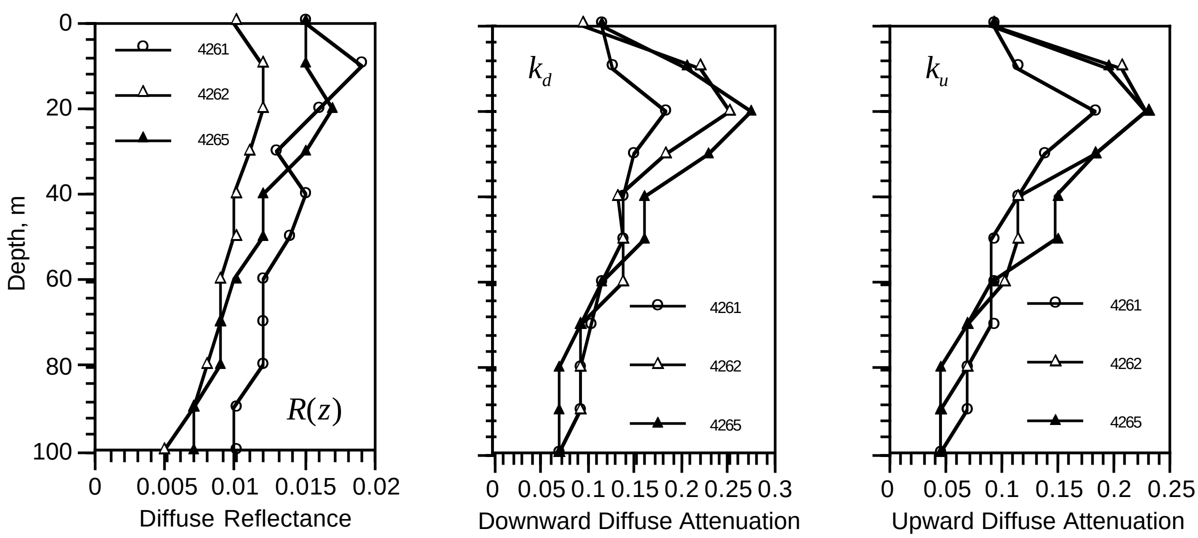

Figure 3. Diffuse reflectance $R(z)$, downward k_d and upward k_u diffuse attenuation coefficients ($\lambda = 450$ nm) at stations 4261, 4262 and 4265.

4.0 BIOLOGICAL PROPERTIES

Chlorophyll ‘a’ and phaeopigments (phaeophytin ‘a’ and ‘phaeophorbid ‘a’) concentrations were estimated by two methods: fluorometric determination of pigments in acetone extracts (stations from 4231 to 4246) and by a contact method of active (luminescent) sounding (stations from 4247 to 4266). Samples of seawater for determination of chlorophyll in acetone extracts were collected with plastic bathimeter of a flow-through type or with a cluster of bathimeters included in a suit MHI 4102. The sampling depths for seawater were chosen from water temperature profiles with the goal to better resolve profiles of chlorophyll pigments *above*, *in*, and *under* a thermocline.

Filtration of samples was made with a membrane filter with a pore diameter about 0.6 μm. Pigments were extracted with 90% water-dissolved acetone during at least 20 hours at 4°C. Fluorescence of extracts before and after acidization by 2NHCl was measured with a fluorimeter attachment to a spectrocolorimeter SPECOL. Determination of chlorophyll and phaeopigment concentrations was made with methodology proposed by Gibbs (1979).

In situ determination of chlorophyll ‘a’ concentration was made by submersible laser pulse fluorimeter developed at the Optics Department of MHI UAS. The calibration of the fluorimeter was made using conventionally measured chlorophyll concentrations from discrete samples. Before switching to *in situ* measurements we reliably established a correspondence of the *in situ* fluorescence with the *in vivo* (in cuvette) fluorescence.

Determination of phosphates was made according to the Morphy and Rayley method (Sapozhnikov, 1978). The total chlorophyll profiles at several stations are given in Fig. 4. Tables of chlorophyll, phaeopigments, and phosphates concentrations for a number of depths at all stations are given in Nelepo (1985).

5.0 EMPIRICAL RELATIONSHIPS BETWEEN OPTICAL AND OPTICAL AND BIOLOGICAL PROPERTIES OF BLACK SEA WATERS

Results of the shipborne measurements presented in previous sections allow us to derive regression relationships between some optical and optical and biological properties of seawater.

5.1. Relationships between Secchi disk visibility depth and surface chlorophyll concentration

We derived two relationships between Secchi disk visibility depth z_s and subsurface chlorophyll ‘a’ concentration C_c, and z_s and subsurface total chlorophyll concentration C_{c+ph} (Chlorophyll ‘a’+phaeophytin ‘a’). They are:

$$C_c = C_{0c} \exp(-z_s / z_{0c}), \quad C_{0c} = 7.489\,\mathrm{mg/m^3}, \quad z_{0c} = 4.5713\,\mathrm{m}, \quad r^2 = 0.816, \tag{1}$$

$$C_{c+ph} = C_{0\Sigma} \exp(-z_s / z_{0\Sigma}), \quad C_{0\Sigma} = 11.043\,\mathrm{mg/m^3}, \quad z_{0\Sigma} = 4.5142\,\mathrm{m}, \quad r^2 = 0.852. \tag{2}$$

As it should be expected, the correlation between total chlorophyll and Secchi disk visibility depth is stronger.

5.2. Relationships between Secchi disk visibility depth and color indices

We have the following correlations between color indices at 1 and 6 m and Secchi disk visibility:

$$J(1\,\mathrm{m}) = 11.043 \exp(-z_s / z_{01}), \quad z_{01} = 1.045\,\mathrm{m}, \quad r^2 = 0.812, \tag{3}$$

$$J(6\,\mathrm{m}) = 9.915 \exp(-z_s / z_{06}), \quad z_{06} = 5.853\,\mathrm{m}, \quad r^2 = 0.916. \tag{4}$$

As it is anticipated, the second correlation (4) is much stronger than the first one (3).

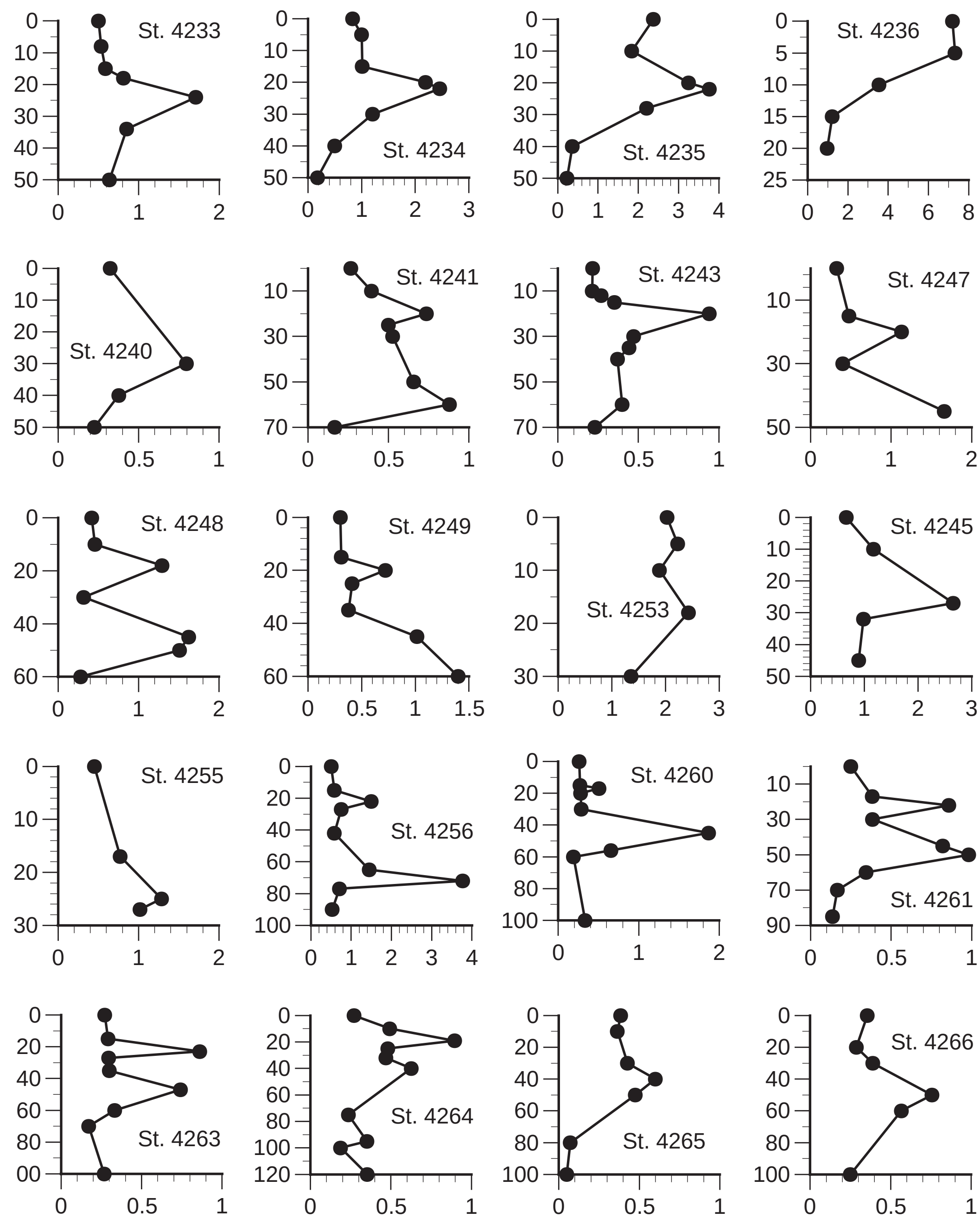

Figure 4. Total chlorophyll concentration in g/l (horizontal axis) as a function of depth (in m).

5.3. Relationships between color indices and surface chlorophyll concentration

The relationships between color indices measured at 1 and 6 m and total surface chlorophyll concentration C_{c+ph} are not as good as correlations (1)-(2):

$$C_{c+ph} = 0.844\, J_{(1\text{m})}^{1.4612},\ r^2 = 0.617, \quad (5)$$

$$C_{c+ph} = 0.560\, J_{(6\text{m})}^{1.1134},\ r^2 = 0.734, \quad (6)$$

but the second relationship (6) may be still useful.

5.4. Relationships between surface beam attenuation coefficients at different wavelengths and surface chlorophyll concentration

In order to investigate wavelength dependence we correlated surface beam attenuation coefficients at all six channels with surface total chlorophyll concentration:

$$C_{c+ph} = C_{c0\lambda} \exp[c(\lambda,0) / c_{0\lambda}], \qquad (7)$$

where the coefficients are given in Table 2.

Table 2. Coefficients of regressions $C_{c0\lambda}$ and $c_{0\lambda}$ and mean-square errors r^2 for Eq. (7).

coefficients \ λ, nm	422	453	493	528	590	625
$C_{c0\lambda}$, mg / m^3	0.1613	0.16212	0.18403	0.15649	0.14801	0.16188
$c_{0\lambda}$, m^{-1}	0.0332	0.0299	0.0333	0.0280	0.0270	0.0330
r^2	0.7736	0.7640	0.6755	0.8092	0.8170	0.5214

It is evident that the most promising channel for Eq. (7) is a 590 nm channel.

5.4. Relationships between averaged beam attenuation coefficients at different wavelengths and averaged chlorophyll concentration

In order to improve regressions presented in previous subsections we correlated the averaged beam attenuation coefficient with the averaged total chlorophyll concentration. We used the following procedure of averaging that is independent on any *a piori* information:

$$\langle C_{c+ph} \rangle_\lambda = (1/z_{\max}) \int_0^{z_{\max}} C_{c+ph}(z) \exp[-c(z,\lambda) z] dz, \qquad (8)$$

$$\langle c \rangle_\lambda = (1/z_{\max}) \int_0^{z_{\max}} c(z,\lambda) \exp[-c(z,\lambda) z] dz. \qquad (9)$$

This time averaged total chlorophyll concentration is connected with an average beam attenuation coefficient with a slightly more complex equation:

$$\langle C_{c+ph} \rangle_\lambda = C_{0\lambda} \exp[-\alpha_\lambda \langle c \rangle_\lambda^2 + \beta_\lambda \langle c \rangle_\lambda], \qquad (10)$$

where coefficients of regression and errors are given in Tab. 3.

Table 3. Coefficients of regressions $C_{0\lambda}$, α_λ and β_λ, and mean-square errors r^2 for Eq. (10).

coefficients \ λ, nm	422	453	493	528	590
$C_{0\lambda}$, mg / m^3	7.934E-3	9.700E-3	1.2566E-2	1.28863E-2	1.73598E-2
α_λ, m^2	101.5962	140.3656	150.8658	199.2103	229.2228
β_λ, m	45.66164	53.83547	52.33970	57.84135	58.88051
r^2	0.9233	0.9372	0.8859	0.8656	0.7740

Table 3 shows that averaging over beam attenuation profile significantly improves correlation between total chlorophyll concentration and beam attenuation profile. The correlation coefficient $r^2 = 0.9372$ for channel with $\lambda = 453$ nm may be regarded as very good.

6.0 CONCLUSION

The partial analysis of results of shipborne marine part of a multilevel airborne and sea-truth experiment (Nelepo et al., 1985; Urdenko et al., 1985a, 1985b) shows that these results may be used not only to refine existing models of the radiative transfer of light in the sea-atmospheric system but also to enhance algorithms of retrieving optical and biological properties of the upper photic sea layer. The relationships (1)-(2), (7) and (10) may be used as regional sea truth correlations between optical and biological properties of Black Sea.

7.0 ACKNOWLEDGMENTS

One of the authors is thankful for continuing support at the Naval Research Laboratory through the programs SS 5939-A9 and LOE 6640-09. The authors are grateful to D. N. Gvozdeva, S. F. Korchagina, M. A. Krasheninnikova, N. V. Soldan, L. O. Sukhovnina, and L. N. Zolotova for help. This article represents NRL contribution PP/7331–98–0039.

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