

SPACE VARIABILITY OF OCEAN COLOR INDEX AND ITS CONNECTION WITH BIOLOGICAL AND DYNAMIC FACTORS*

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ABSTRACT

This paper discusses the results of two decades of *in situ* measurements of the ocean color index, which is defined as the ratio of two upward light radiances measured at nadir at both 540 and 420 nm. An optical classification of ocean waters based on the color index is proposed. This classification is compared to other optical water classifications. The color index distributions for specific regions of interest were compiled and compared with the water dynamics. The ranges of the color index variability were also estimated for these ocean regions. It was shown that the color index regressions can be successfully used for the interpretation of spaceborne and airborne optical remote information.

1.0 INTRODUCTION

During the 1970's and 80's the color index (CI) was routinely measured in different regions of the world ocean in the expeditions conducted by the Marine Hydrophysical Institute (MHI) of the Ukrainian National Academy of Sciences. The color index is defined as the ratio of the two upward light radiances measured at nadir at two wavelengths: 540 and 420 nm. It was measured with a special photometer installed in a vertical shaft going through the hull of the research vessel. The measurements were made during the daytime both at stations and underway. An extensive data set has been collected during more than twenty years of marine expeditions. It includes the geographical distribution of the color index and relationships of the color index with biological and dynamic factors. The color index is a good descriptor of the seawater spectral reflectance. For the wavelengths cited above, the color index is also a good indicator of the ocean primary biological productivity. A regression equation derived in this paper connects the color index with the chlorophyll concentration in the euphotic zone. For "Case 1" waters, the color index is also closely related with other biooptical properties of the upper ocean layer. The range of the color index variability is about three orders of magnitude. This makes color index a very sensitive indicator of the biooptical state of the ocean euphotic zone.

2.0 COLOR INDEX

The color index was introduced in publications by Clark (1970) and Jerlov (1974). In a short time it became widely accepted in hydrooptical investigations. The color index is the property that determines the spectral reflectivity of the ocean water. It is defined as the ratio of radiances of the light backscattered by the ocean water column at two different wavelengths λ_1 and λ_2 . These

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radiances are measured at nadir just below the sea surface, *i.e.*,

$$I(\lambda_1, \lambda_2) = L_{\uparrow w}^0(\lambda_1) / L_{\uparrow w}^0(\lambda_2). \quad (1)$$

In the two-flow approximation to the radiative transfer, (Haltrin, 1985, 1997; Haltrin and Kattawar, 1993), the spectral radiance of the light ascending from the sea $L_{\uparrow w}^0(\lambda)$ is determined by Gordon's parameter $x(\lambda)$:

$$L_{\uparrow w}^0(\lambda) \propto x(\lambda), \quad x(\lambda) = b_B(\lambda) / [b_B(\lambda) + a(\lambda)], \quad (2)$$

where $b_B(\lambda)$ is the backscattering coefficient, and $a(\lambda)$ is the absorption coefficient.

In the open ocean the spectral radiance $L_{\uparrow w}^0(\lambda)$ is proportional to the parameter $x(\lambda)$ and the backscattering coefficient is much smaller than the absorption coefficient. Therefore the color index can be determined by the equation:

$$I(\lambda_1, \lambda_2) = [b_B(\lambda_1) / b_B(\lambda_2)] [a(\lambda_2) / a(\lambda_1)]. \quad (3)$$

With the proper choice of the spectral wavelengths λ_1 and λ_2 the color index is a good indicator of the biological productivity of oceanic waters. In practice, one of these wavelengths is chosen to be in the violet part of the phytoplankton absorption band. The second wavelength is chosen outside of this band, in the green part of the spectrum. With such choice of wavelengths and if $\lambda_1 > \lambda_2$, the color index increases with the increase of phytoplankton concentration. This is mainly due to the stronger increase in the absorption coefficient in the violet part of the spectrum than in the green one. The biological part of the absorption coefficient is a sum of the absorption coefficients by the phytoplankton and dissolved organic matter or "yellow substance". Because in the open ocean the "yellow substance" is primarily the result of decay of the dead plankton species, its concentration increases with the increase of the phytoplankton concentration. The spectral absorption of the "yellow substance" exponentially decreases with the increase of the wavelength: $a_Y^0(\lambda) \propto \exp(-k_Y \lambda)$, with $k_Y \sim 0.015 \text{ nm}^{-1}$. This means that the "yellow substance", like the phytoplankton, absorbs the violet light stronger than the green one. The second factor that leads to the increase of the color index with the increase of phytoplankton concentration is due to the backscattering coefficient. The increase in the concentration of the phytoplankton is usually connected with the increase of the relative share of large phytoplankton particles. The backscattering by the large particles is less selective than the backscattering by the small particles. This means that the exponent n in the relation $b_B(\lambda) \propto \lambda^{-n}$ is smaller for the big scattering particles. This amplifies the effect imposed by the absorption coefficient.

We conclude that the effects, which are due to absorption and backscattering, make the color index a very sensitive indicator of the biological productivity. The range of variability of the color index is more than two orders of magnitudes when passing from the low-productivity (oligotrophic) to the high-productivity (eutrophic) waters.

One of the important features of the color index is its ability to be measured underway from a research vessel (RV). This allows the collection of abundant hydrooptical information without stopping the ship. Such measurements can be accomplished by a contact method, by placing the meter into an opening through the hull, available on some of the research vessels. The color index can also be measured remotely underway with the simultaneous corrections on the specularly reflected skylight. The remote measurements also can be done from airborne platforms when the appropriate atmospheric corrections are made (Haltrin, 1996).

2.1. The *in situ* Measurements of the Color Index

In the 1970's and 1980's the Marine Hydrophysical Institute routinely measured the color index during its regular expeditions in different areas of the world ocean. The measurements were made by an automatic probe installed underwater in the vertical shaft piercing the hull of the RV "Akademik Vernadsky". Such an installation allowed for the collection of color index data not only on oceanographic stations but also underway at any level of sea surface waviness. On the MHI ships without such a shaft the onboard probes were used.

From the definition given above, the color index should be measured just below the sea surface. But in practice, in marine expeditions it is almost impossible to carry out such measurements, especially because of the sea surface waviness that is always present. For these reasons the "undersurface" measurements are always carried out at depths from 0.5 to 1 m. In several MHI expeditions 321 inter-calibration measurements of the color indices $I_{(z=1m)}$ and $I_{(z=6m)}$ were made. During these measurements almost identical probes were installed in different locations on the research vessel. One probe was submerged at 1 m depth from the board of the ship. The other one was placed at 6 m depth in the shaft going through the hull of the ship. This set of color indices cover almost all possible range of variability of this parameter in the open ocean (from 0.035 to 10 for $I_{(z=6m)}$). In the transparent waters the color indices vary in the range between 0.035 to 0.5. In such waters the values of the color indices measured at 1 and 6 m depths are almost indistinguishable. When the turbidity of water increases, the systematic increase of the $I_{(z=6m)}$ in comparison with the $I_{(z=1m)}$ was detected. The relationship between these indices for the $I_{(z=1m)} > 0.5$ is given by the following regression (Vladimirov *et al.*, 1987):

$$I_{(z=1m)} = 0.746 I_{(z=6m)}^{0.82}. \quad (4)$$

Routine measurements of the color index carried out in different spectral bands in many expeditions were made by the MHI probes. With the onboard submersible probe such measurements were carried out at the 550 and 440 nm at the depth of 6 m below the sea surface. With the submersible probe, used through the opening in the hull of the ship, the measurements were made at 540 and 420 nm. The statistical comparison of these color indices gives the following relationship (Vladimirov *et al.*, 1987):

$$I(550, 440) = 0.88 I(540, 420)^{1.09}. \quad (5)$$

In this paper, as in the previous ones (Afonin *et al.*, 1980; Man'kovsky, 1980; Vladimirov *et al.*, 1987), when we simply mention the color index, we mean the value of the $I_c \equiv I(550, 440)$ measured at the depth of 6 m. The optical calibrations of all our color index probes were made in clear weather with the white Lambertian diffuse reflector that was illuminated by the light of the sun and the sky. The color index of the light reflected from this white Lambertian surface was set equal to 1.

2.2. Color Index and Chlorophyll Concentration

One of the main goals of the color index measurements carried out by the MHI was to find out the quantitative relationship between the color index and the concentration of phytoplankton. Numerous joint measurements of the color index and the concentrations of chlorophyll-*a* in the probes taken in the Atlantic Ocean from the upper mixed layer of "type 1" waters have been made. As a result, the following regression relationship which is based on 175 samples, was derived (Afonin *et al.*, 1980):

$$C_{chl-a}, mg/m^3 = 0.29 I_c^{0.74}. \quad (6)$$

The correlation coefficient in Eqn. (6) is equal to 0.86 ± 0.04 . The relative mean square error for the prediction of the chlorophyll concentration is about 80%.

Similar measurements (160 probes) were made in the Indian Ocean. They give almost the same relationship:

$$C_{chl-a}, mg/m^3 = 0.26 I_c^{0.73}. \quad (7)$$

The correlation coefficient in this experiment is 0.89 ± 0.02 , and relative mean square error for the prediction of the chlorophyll concentration is about 50%. The range of variability of the chlorophyll concentrations used to derive Eqns. (6)-(7) was from 0.02 to $4.0 mg/m^3$.

The errors for the chlorophyll concentration prediction with the Eqns. (6)-(7) are determined by the following factors:

1. Chlorophyll concentration was measured only from the water samples pumped from one 6 m depth level. The vertical distribution of the chlorophyll was not measured.
2. The effective water layer depth that shapes the upwelling light radiance detected by the probe changes from location to location. This depth is approximately equal to the Secchi disk visibility depth. It means that the effective depth varies in the range from several tens of meters in clear ocean waters to several meters in the waters with high phytoplankton concentration.
3. The presence of other particles, like detritus and terrigenous mineral matter, in seawater also influences the values of the color index.
4. The specific chlorophyll-*a* content in the phytoplankton cells may vary several times depending on the kind of species and their physiological condition.
5. The methodological errors in determining the chlorophyll content are about 20%.

2.3. Color Index and Secchi Disk Visibility

The color index also has very highly correlated dependencies with the Secchi disk visibility depth z_s :

$$I_c = -0.07 + 150/z_s^2. \quad (8)$$

The correlation coefficient is equal to 0.93 ± 0.02 and the variability for the Secchi disk visibility depth is in the range of $5m < z_s < 40m$. The number of measurements was 112.

The correlation with the water color N_{cs} according to the standard Forel-Uhle scale is:

$$I_c = 0.00654 N_{cs}^{2.67}. \quad (9)$$

The correlation coefficient in Eqn. (9) is 0.97 ± 0.02 , with the range of variability for water color $2 < N_{cs} < 18$. The number of measurements was 60.

The high correlation coefficients between the color index and the Secchi disk visibility depth and water color can be explained by the fact that all these properties are determined by the integral effects of absorption and scattering in the water layer between the sea surface and down to $3z_s$.

3.0. OPTICAL CLASSIFICATION OF WATERS BASED ON COLOR INDEX

Based on the analysis of color index measurements and their relationships with biological and optical properties, the MHI optical classification of ocean waters was developed (Man'kovsky, 1980). The "Case 1" ocean waters were subdivided into seven types (see Table 1). Each water type was associated with the ranges of variability of the following three parameters: the Secchi disk visibility depth, the water color according to the standard Forel-Uhle color scale, and the chlorophyll-*a* concentration in the upper mixed layer of the ocean.

Table 1. Optical classification of ocean waters based on the color index.

Water Type	Color Index $I(550,440)$ at $z = 6m$	Secchi disk visibility z_s, m	Standard scale water color, tube number	Chlorophyll- <i>a</i> concentration, mg / m^3
1	< 0.05	> 35	1 - 2	< 0.03
2	0.05 - 0.15	35 - 26	2 - 3	0.03 - 0.07
3	0.15 - 0.50	26 - 16	3 - 5	0.07 - 0.18
4	0.50 - 1.50	16 - 10	5 - 7	0.18 - 0.40
5	1.50 - 3.00	10 - 7	7 - 10	0.40 - 0.70
6	3.00 - 6.00	7 - 5	10 - 13	0.70 - 1.10
7	> 6.00	< 5	> 13	> 1.10

This optical classification of ocean waters, based on the color index, has an advantage over the other classifications connected with the vertical diffuse attenuation coefficient of daylight (Jerlov, 1974; Pelevin and Rutkovskaya, 1977). This classification is advantageous because the color index can be measured underway of the ship and from low-flying airborne platforms. This allows the assessment and mapping of large oceanic aquatories in real time. It is necessary to note, that our optical classification is not restricted to some arbitrary chosen water layer, as the 0-10 *m* layer in Jerlov's classification or the 0-100 *m* layer in Pelevin's classification. Our classification depends on the effective undersurface ocean layer that forms the light field upwelling from the ocean. The thickness of this layer is approximately equal to the Secchi disk visibility depth.

Pelevin (1980) investigated the connection of the diffuse attenuation coefficient for 500 *nm* wavelength, averaged over the upper 100-*m* ocean layer, with the color index $I_c \equiv I(550,440)$. He found the following relationship between them:

$$\langle k_d(500) \rangle_{0 < z < 100} = 0.023 + 0.0851 I_c. \quad (10)$$

The mean square deviation in this equation is equal to 14%. Equation (10) can be used to restore the average diffuse attenuation coefficient $\langle k_d(500) \rangle$. The values of diffuse attenuation coefficient allow to restore the spectral distribution of the diffuse attenuation coefficient through spectral regression equations given in the paper by Pelevin (1983).

4. 0. RELATION OF THE COLOR INDEX TO THE OCEAN DYNAMICS

Table 2 gives examples of the color index values measured in various MHI expeditions in different areas of the world ocean. This table shows that the color index is strongly related to the water dynamics that determines the productivity of the area. The minimal values of the color index are observed in the areas with the anticyclone circulation and in convergence zones (Sargasso Sea, south subtropics convergence area in the Indian Ocean). The maximum values of CI are observed in coastal upwelling regions similar to those located near the shores of Africa and South America.

An example of the coupling with the water dynamics is shown in Fig. 1. The figure shows the distribution of the color index over the tropical polygon. Those data were obtained in the 47-th expedition of the RV "Mikhail Lomonosov" (July-September, 1986) carried out under the "Razrezy" (Slices) project. The larger values of the color index were detected in the divergence zone of the south tradewind current. In the eastern part of the ocean this current splits into several streams that flow in the southern and northern directions. In the northeastern part of the polygon the area of the cyclone eddy is created by the branches of the mid-tradewind counter current and the northern tradewind current. This area also shows the high values of the color index. At the same

Table 2. Values of the color index I(550,440) in some areas of the world ocean.

No.	Location	Most frequent	Minimal	Maximal
<i>Atlantic Ocean</i>				
1.	Sargasso Sea	0.04	0.025	0.07
2.	Central part, tropical areas	0.10	0.035	0.45
3.	Along Africa coast from Gibraltar to West Sahara	0.50	0.12	1.50
4.	Area of Cape Blank	1.40	0.40	20.0
<i>Caribbean Sea</i>				
1.	Northern part (to N from 15° Northern Latitude)	0.15	0.03	0.75
2.	Southern part (to S from 15° Northern Latitude)	0.40	0.04	9.00
<i>Mediterranean region</i>				
1.	Gibraltar Strait	0.40	0.26	0.90
2.	Ionic Sea	0.20	0.11	0.27
3.	Aegean Sea	0.30	0.24	2.00
4.	Marmara Sea	2.50	0.53	11.0
5.	Black Sea	2.00	0.30	4.0
<i>Red Sea</i>				
1.	Northern and central area of deep sea	0.07	0.025	0.16
2.	Southern area of deep part	0.40	0.20	0.75
<i>South Ocean</i>				
1.	Along 20° East Long. from 35° to 55° South. Lat.	0.30	0.12	1.3
<i>Indian Ocean</i>				
1.	Arabian Sea, Center and Eastern area of deep part	0.10	0.03	0.30
2.	Along Somalia coast	0.40	0.20	7.60
3.	Bengal Bay, deep part	0.10	0.08	0.20
4.	Equatorial zone, $\pm 2^\circ$	0.10	0.05	0.20
5.	Zone of southern subtropic convergence	0.05	0.028	0.08
<i>Pacific Ocean</i>				
1.	Tropical area of the central part	0.15	0.10	0.28
2.	Tropical area of the western part	0.15	0.05	0.19
3.	Along South Amer. coast, from Panama to Callao	0.60	0.34	14.0

time, in the areas with the anticyclone water movement and in the convergence zones of the north tradewind branches and mid-tradewind counter-current, the color indices were minimal.

Another example that shows the influence of water dynamics on the distribution of the color index is given in the inset of Fig. 1. It shows the distribution of the optical water types in the Caribbean Sea in the fall and winter seasons. These data were collected in 1971-1985 during the expeditions conducted under the international SICAR and MOCARIB projects (Bulgakov *et al.*, 1991). The global western influx of waters in the Caribbean Sea, caused by the north tradewind current coming from the straits of Lesser Antilles, causes a general rise in the water level at the southern part of the sea with the decline of the water level in the northern part. In the southern part of the sea to the west of the Caribbean current, which flows from the Lesser Antilles to the Bay of Yucatan, the cyclonic circulation of waters is predominant. There are also strong near-shore upwellings there. In the northern part of the sea, to the right of the Caribbean current, the anticyclone circulation is predominant. As a result, the southern parts of the sea have higher biological productivity than the northern ones. The mentioned effects influence the distribution of the color index: its values are higher in the southern part. The high values of the color index (which correspond to the water of type of 4), that have been measured in the Gulf of Mexico, are located

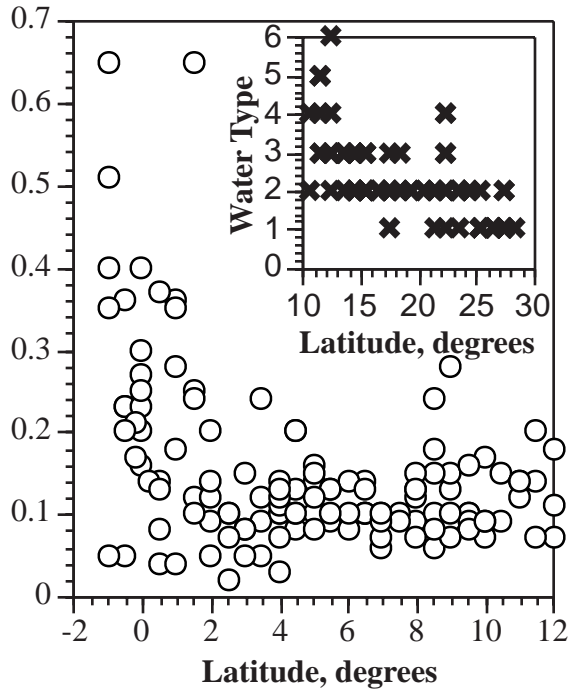


Fig. 1. Spatial distribution of the color index in the tropical polygon and of the water type in the Caribbean sea (inset).

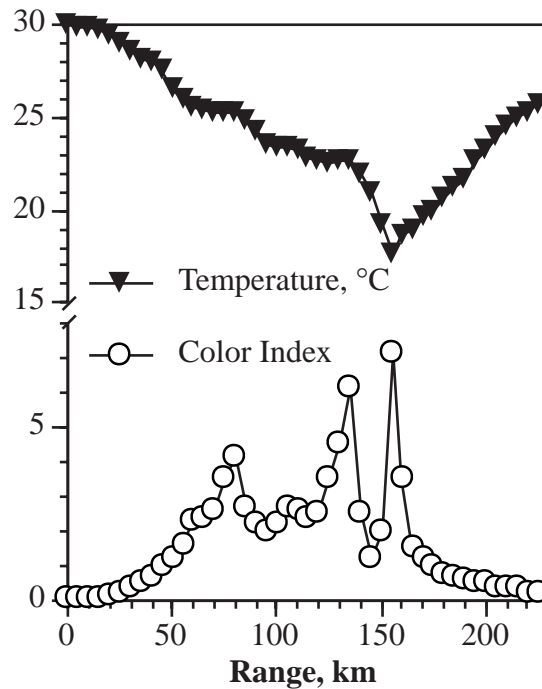


Fig. 2. Spatial distribution of the color index and water temperature in the Caribbean Sea in the Somalia current.

near the Campeche bank. The low values of the color index (water type 1) are distributed over the southwestern part of the Sargasso Sea that is located in the northern subtropic anticyclone circulation.

An excellent example of utilizing the color index to obtain additional oceanologic information is shown in Fig. 2. It shows the distribution of the color index and the temperature over the route crossing the Somalia current that develops in the Indian Ocean in the summer monsoon season. The measurements were made with the probes installed in the shaft of the RV "Akademik Vernadsky" across the current in the area of Cape Guardafui.

In the summer monsoon period, as a result of complex interaction of the southwest monsoon wind with the Somalia current, some very interesting upwellings are created. The distributions of the color index and temperature, which are displayed in Fig. 2, show that this current has several areas of upwelling. The distances between these upwellings decrease with the increase in the distance from the shore. It is known that such phenomenon exists in the near-shore currents (Latun, 1984). The existence of several upwelling zones can be explained by the hydrodynamic instability of the current. The instability causes a complex transverse circulation. This circulation consists of the mixture of eddies with an opposite circulation. The horizontal axes of rotation of these eddies are parallel to the direction of the current. As a result, the sequence of the upwelling and downwelling areas shows up in the current that flows along the shore. The areas decrease in size in the direction from the shelf zone to the continental slope.

8. 0. CONCLUSION

An optical classification of the ocean waters based on the color index is proposed and compared with other optical water classifications. The proposed optical classification of ocean waters has an advantage over other classifications, which are based on the diffuse attenuation

coefficients. This advantage consists in the ability to measure the color index underway without stopping the ship or from low-flying airborne platforms. This allows the real-time assessment and mapping of large oceanic aquatories.

5.0. ACKNOWLEDGMENTS

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