On the relation between the visibility depth of a white disk, optical index of water type, and water circulation in the Atlantic Ocean

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Experimental data on the visibility depth of a white disk Z_δ and the optical index of water type m for surface water of the Atlantic Ocean are analyzed. The comparison made between the Z_δ and m maps of the Atlantic Ocean with those for the dynamic depth D at the 100 m level indicates that the large values of Z_δ and small values of m occur under conditions of anticyclone circulation. Turbid water is typical of the cyclone circulation, which is associated with the ascent of low-layer water enriched with nutrients. The empirical equation $Z_\delta = Z_\delta(m)$ derived allows estimation of Z_δ to be done from the values of m measured remotely in the visible spectral region from a ship, airplane, or satellite.

In the literature, one can find a huge amount of measurements of the depth of the white disk visibility Z_δ, because the value of Z_δ can be easily measured from any ship and under almost any conditions. The data on Z_δ are summarized in the *Atlas of Oceans*.[1,2] The value of Z_δ gives an idea of the cleanness of waters, but this idea is quite an arbitrary and for this reason this parameter is referred to as the "relative transparency" of water.

The optical index of water type m is a more informative parameter. In Refs. 3 to 6 it was shown that, knowing m for a given water area, it is possible to estimate the spectral composition of light at different depths and to obtain approximate data on the concentration of phytoplankton chlorophyll, dissolved organic matter (DOM), and the total suspended matter in the open ocean. The experimentally obtained data on m for three oceans have been published in Refs. 7 and 8. Nevertheless, it should be noted that not all regions of the Global Ocean are covered by these data; the data on m are much less voluminous than the data on Z_δ.

There is an obvious relation between these parameters, because the index m characterizes the depth of sunlight penetration into the water at the wavelength λ = 500 nm ($m = 43.43K_{d_{500}}$, where $K_{d_{500}}$ [Ref. 9] is the extinction coefficient for the radiation along the vertical direction at λ = 500 nm). On the other hand, the more transparent is the water for the sunlight, the larger is the depth of the white disk visibility Z_δ.

There is a voluminous literature about the dependence of the depth of white disk visibility on the hydrooptical characteristics of water (see, for example, Ref. 10). Omitting thorough analysis of this dependence, we shall make an attempt to find the general relation between Z_δ and m, which would allow determination of m from known Z_δ with a sufficient accuracy.

The observed contrast K between the brightness of a submerged white disk and the background, related to the background brightness, can be estimated as:

$$K = \frac{E_0 \exp[-(K_d + \varepsilon)]z}{E_0 \rho \pi^{-1}}, \quad (1)$$

where z is the depth of submergence of a white scatterer; K_d is the vertical sunlight extinction coefficient; ε is the extinction coefficient for the visible brightness of a disk with small angular size; ρ is the water surface brightness coefficient; E_0 is the sunlight irradiance of the water surface; $E_0 e^{-K_d z}$ is the irradiance of the disk submerged to the depth z; the exponent $e^{-\varepsilon z}$ accounts for the extinction of the visible brightness of the disk with a small angular size observed from the zero depth. By definition $E_0\rho\pi^{-1}$ is the observed sea brightness, that is, the background. The contrast K will be defined as a brightness increment along the direction toward the disk, created by the reflection of sunlight from the disk surface, related to the background. All the parameters in Eq. (1) correspond to a certain wavelength, that is, have a spectral character.

The disk becomes invisible for an observer, when the visible contrast decreases down to the threshold, for the human eye, value $K_{\min}$. By definition, this occurs when the depth of submergence of the white disk is Z_δ.

Substituting the minimum observable contrast and the depth of white disk visibility Z_δ as z into Eq. (1) and taking all the characteristics at the central part of the visible spectrum, that is, at about λ = 500 nm, we obtain the following semiempirical dependence:

$$K_{\min} = \pi e^{-(K_{d_{500}} + \varepsilon_{500}) Z_\delta} / \rho_{500}. \quad (2)$$

Taking into account that, roughly, $\varepsilon_{500} = \xi K_{d_{500}}$ [Ref. 11], where ξ is a statistically determined

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coefficient, and assuming K_{min} = 0.02 (that is, 2%), $\rho \cong 0.02$ (variable only slightly in different waters at the wavelength of 500 nm), we can estimate Z_δ:

$$Z_\delta = \frac{-\ln(K_{min}\rho_{500} / \pi)}{K_{d_{500}}(1+\xi)} = \frac{\tilde{N}}{m}. \qquad (3)$$

Substituting the above mean values of K_{min} and ρ_{500} and varying ξ, we obtain the values of C presented in Table 1.

Table 1. Values of the coefficient *C* in Eq. (3)

ξ	C, m	Notes
4.0	77	Extremely clean oceanic water
6.0	55	Typical clean oceanic water (zones of weak anticyclone circulation)
7.0	49	Typical oceanic water (zone of weak cyclone circulation)

As follows from Table 1 the mean value of the coefficient C is $C \cong 50$ m for typical surface water of the open ocean. Hence, we have the equation for practical use:

$$Z_\delta = 50 / m. \qquad (4)$$

Let us check this equation using the available experimental data on m and Z_δ obtained in the Atlantic Ocean in different research missions and in different seasons presented in the form of maps.[1,7,8] For quantitative analysis, we also used the maps of the dynamic depth D (in conditional dynamic meters) at the 100 m level, characterizing the circulation in the Atlantic Ocean.[1] These maps are quite bulky, and therefore these are omitted in this paper.

From the analysis of the experimental data, we showed[12] that the distribution of the optical index of surface water type m, characterizing the water transparency, in the Atlantic Ocean is formed under the effect of dynamic factors, namely, oceanic currents and is related to the circulation of oceanic water, which is characterized by the dynamic depth D. It is quite natural to expect that the same factors are also decisive for the distribution of the depth of white disk visibility Z_δ. Actually, the comparison of the distributions of Z_δ and the surface water circulation confirms this assumption. As in the case of m and D distributions, the Z_δ isolines in the map of the Atlantic Ocean to the north from 40°N are elongated from the southwest to the northeast and coincide with the Gulf Stream and the North Atlantic Current, as well as with the Norwegian Current near the European coasts. In the 40°N–40°S latitudinal belt, common features are also observed in the fields of m, D, and Z_δ. This zone is bounded by the system of currents: Gulf Stream and North Atlantic Current in the north; Canaries, Guinea, and Benguela Currents near the western coast of Africa; West Wind Current around the Antarctic; Brazil, Guiana, and Caribbean Currents near the eastern coast of South America.

Inside this vast closed zone of transparent water, smaller closed zones of even more transparent water are observed. These zones are formed at the centers of anticyclone vortices. The coordinates of the centers of these zones in the field of Z_δ almost coincide with the coordinates of the centers of the analogous zones in the fields of the water type index m and the dynamic depth D. It should be emphasized that this coincidence of the centers of the dynamic characteristics and the transparency characteristics in the structure of their fields points to the stability of these formations.

Let us check the qualitative relation between the two transparency characteristics of surface water in the Atlantic Ocean: the water type index m and the depth of the white disk visibility Z_δ, using the distributions of these characteristics.[1,8] Note that these parameters are represented by two independent types of the experimental data sets collected in different time, and therefore we should not expect the exact coincidence between them. Let us analyze the latitudinal profiles of m and Z_δ along the fixed meridional sections in the Atlantic Ocean, at which the whole range of variations of these characteristics and the structure features of their distribution were observed.

We considered three meridional sections in the field of m and Z_δ. Section I is located in the central part of the Atlantic Ocean (l = 32.5°W). Western section II (l = 67.5°W) passes through the Sargasso Sea. Eastern section III (l = 20°W) crosses the Canary Upwelling area. The variability of m for sections I–III is demonstrated in Tables 2–4 and in Fig. 1, along with the latitudinal profile of the optical index of water type m, which was calculated by Eq. (4) from the experimental data on Z_δ along the sections:

$$\tilde{m} = 50 / Z_\delta. \qquad (5)$$

It can be seen from Fig. 1*a* that the most turbid waters with $4.1 \le m < 5.8$ are observed in the region of the Irminger Current (58–60°N). Then section I crosses the zone with $2 \le m < 4.1$, formed by the Gulf Stream and the Labrador Current. In the 35–50°N latitudinal belt, section I crosses the zone with $2.1 \le m < 2.9$, which is formed under the effect of the North Atlantic Current. The vast band of transparent water with $1.5 \le m < 2.1$ in the 34–0°N latitudinal belt is exposed to the effect of the North Atlantic Current and the North Trade Current. To the south, in the 0–25°S latitudinal belt, section I crosses the closed zone of very transparent water, formed by the anticyclone circulation, at the center of which m takes the values of 1.1–1.3. Further to south, the zone of transparent water with $1.5 \le m < 2.1$ is observed at section I. At 40°S this zone is bounded by the West Wind Current. Similar analysis of the latitudinal profile of m, obtained from the data on the depth of white disk visibility Z_δ at the same cross sections, showed quite an identical pattern (Fig. 1*a*). That is, a full agreement is observed both with the dynamic situations in the field of currents and with the latitudinal profile of m. From Tables 2–4 and Fig. 1 we can see that the experimental (m) and theoretically calculated ($\tilde{m}$) values of the optical index of water type almost coincide.

Table 2. Latitudinal profiles of different characteristics of surface water in the Atlantic Ocean along the meridian l = 32.5°W (section I): water type index m [Ref. 8], depth of white disk visibility Z_δ (m) [Ref. 1], water type index $\tilde{m}$ calculated from the observations of Z_δ [Ref. 1] by Eq. (5), and depth of white disk visibility Z_δ (m) calculated from the data on m [Ref. 8] by Eq. (4)

φ°	m	Z_δ	$\tilde{m}$	Z_δ
65°N	4.1–5.3	15	3.3	12
60	2.9–4.1	15	3.3	15
55	2.9–4.1	15	3.3	15
50	2.1–2.9	20	2.5	20
45	2.1–2.9	15	3.1	17
40	2.1–2.9	22	2.2	23
35	1.5–2.1	27.5	1.8	28
30	1.5–2.1	30	1.7	29
25	1.5–2.1	30	1.7	29
20	1.5–2.1	30	1.7	29
15	1.5–2.1	28	1.9	26
10	1.5–2.1	25	2.0	25
5	1.5–2.1	25	2.0	25
0	1.5–2.1	25	2.0	25
5°S	1.3–1.5	30	1.7	33
10	1.1–1.3	35	1.4	38
15	1.1–1.3	35	1.4	38
20	1.3–1.5	35	1.4	36
25	1.5–2.1	30	1.7	29
30	1.5–2.1	30	1.7	29
35	1.5–2.1	28	1.9	26
40	1.5–2.1	25	2.0	25

Table 3. Latitudinal profiles of different characteristics of surface water in the Atlantic Ocean along the meridian l = 67.5°W (section II): water type index m [Ref. 8], depth of white disk visibility Z_δ (m) [Ref. 1], water type index $\tilde{m}$ calculated from the observations of Z_δ [Ref. 1] by Eq. (5), and depth of white disk visibility Z_δ (m) calculated from the data on m [Ref. 8] by Eq. (4)

φ°	m	Z_δ	$\tilde{m}$	Z_δ
42°N	2,1–2,9	15	3,3	17
40.5	2.1–2.9	15	3.3	1.7
40	2.1–2.9	16	3.1	1.7
39	2.1–2.9	20	2.5	20
38	1.5–2.1	25	2.0	25
37.5	1.5–2.1	27.5	1.8	28
37	1.5–2.1	27.5	1.8	28
35	1.3–1.5	32.5	1.5	33
34	1.3–1.5	33.5	1.5	33
32	1.3–1.5	40	1.2	38
30	1.3–1.2	40	1.2	38
28	1.1–1.3	40	1.2	42
25	1.1–1.3	40	1.2	42
23	1.3–1.5	35	1.4	36
20	1.3–1.5	32.5	1.5	33
18	1.5–2.1	32.5	1.5	33
15	1.5–2.1	25	2.0	25
13	2.1–2.9	20	2.5	2

This evidences that the dependence (4) is confirmed by the experimental data. Regularity was found in the behavior of the parameters under study. In Ref. 12 it was shown that the anti-correlation is observed between the values of m and D in all of the sections. This means that the same anti-correlation exists between the values of m and D, and the latitudinal profile of the depth of white disk visibility Z_δ correlates well with the latitudinal profile of circulation (the dynamic height D in conditional dynamic meters at the 100 m level). This can be seen from Fig. 2*a* drawn based on the data[1] for sections I–III.

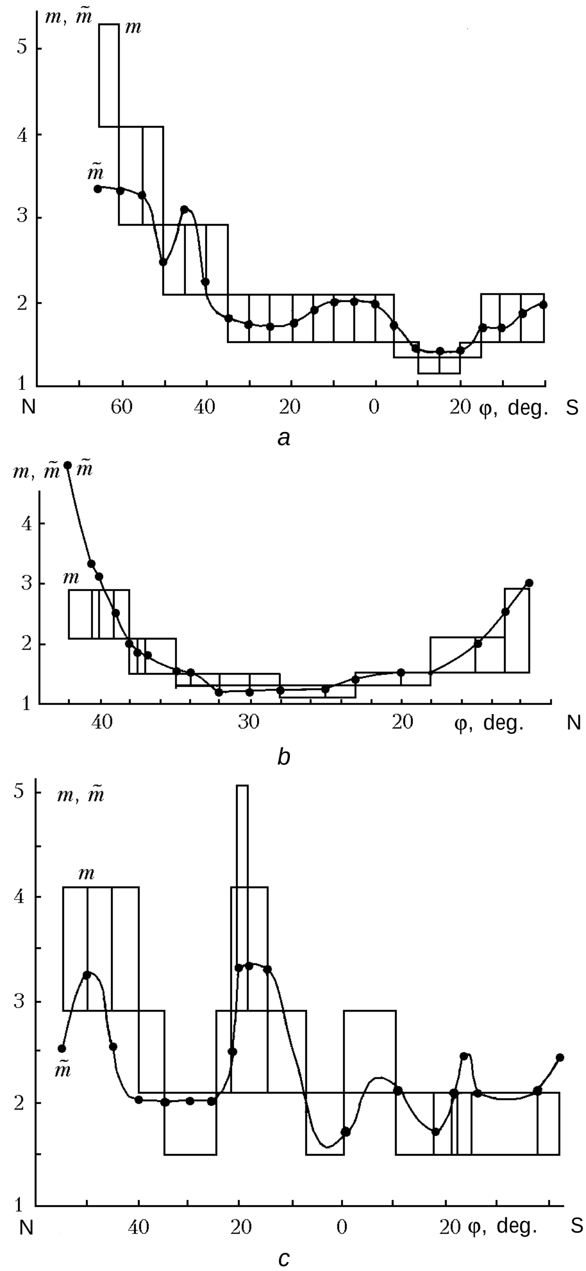

Fig. 1. Latitudinal profiles of water type index m determined experimentally[8] and $\tilde{m}$ calculated from the observations of the depth of white disk visibility Z_δ (m) by Eq. (5) in the Atlantic Ocean along the meridional sections I–III: section I (l = 32.5°W) (*a*); section II (l = 67.5°W) (*b*); and section III (l = 20°W) (*c*).

Consider the latitudinal profile of the parameters at the meridional section II in the Sargasso Sea (see Table 3, Fig. 1*b*). In this case, the section crosses the closed zone of transparent water, which is formed by the anticyclonic circulation under the effect of the Gulf Stream, Antilles Current, and Caribbean Current.

Despite the variability of m, Z_δ, and D is low in this section, there is a complete agreement between the latitudinal profiles of these characteristics, as in section I.

Table 4. Latitudinal profiles of different characteristics of surface water in the Atlantic Ocean along the meridian l = 20°W (section III): water type index m [Ref. 8], depth of white disk visibility Z_δ (m) [Ref. 1], water type index $\tilde{m}$ calculated from the observations of Z_δ [Ref. 1] by Eq. (5), and depth of white disk visibility $\tilde{Z}_\delta$ (m) calculated from the data on m [Ref. 8] by Eq. (4)

φ°	m	Z_δ	$\tilde{m}$	$\tilde{Z}_\delta$
55°N	2.9–4.1	20	2.5	17
50	2.9–4.1	15	3.3	15
45	2.9–4.1	20	2.5	17
40	2.1–2.9	25	2.0	24
35	1.5–2.1	25	2.0	25
30	1.5–2.1	25	2.0	25
25	2.1–2.9	25	2.0	24
22	2.9–4.1	20	2.5	17
20.5	2.9–4.1	15	3.3	12
19	2.9–4.1	15	3.3	15
15	2.1–2.9	15	3.3	15
10	2.1–2.9	20	2.5	20
7.5	1.5–2.1	25	2.0	25
0	2.1–2.9	30	1.7	24
10°S	1.5–2.1	25	2.0	25
17	1.5–2.1	30	1.7	29
21	1.5–2.1	25	2.0	25
22	1.5–2.1	20	2.5	24
25	1.5–2.1	25	2.0	25
38	1.5–2.1	25	2.0	25
42	1.5–2.1	20	2.5	24

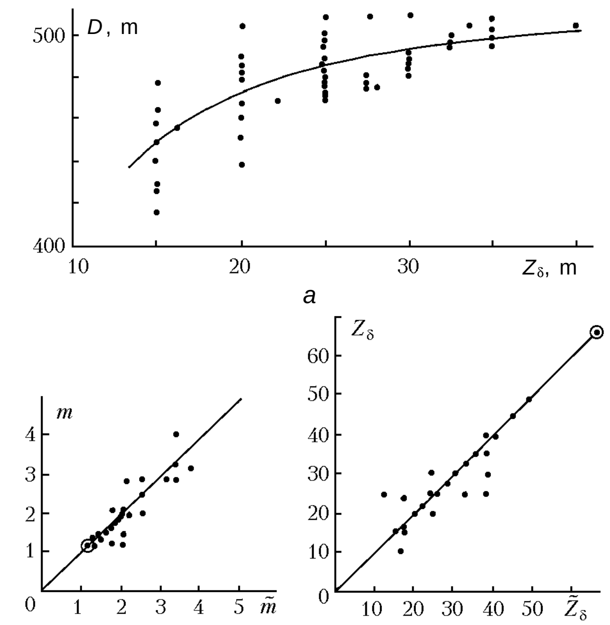

Fig. 2. Regression dependences: $D(Z_\delta)$ (a); $m(\tilde{m})$ (b); $Z_\delta(\tilde{Z}_\delta)$ (c); the circle with a dot denotes the measurement in extremely clean waters of the Pacific Ocean near Cook Islands.

At section III crossing the Canary Upwelling area, waters with different transparency alternate in the field of m, Z_δ, and D (see Table 4 and Fig. 1c). In the 60–40°N latitudinal belt, the effect of the North Atlantic Current is noticeable. The Canary Upwelling (23–8°N) is clearly seen in the latitudinal profiles of the parameters studied; the zones of more transparent water are located to the north and south of the Canary Upwelling. The water in the 0–10°S zone is less transparent, and a vast zone of typically clean ocean water is observed at section III to the south of 10°S to 40°S. This complex structure of the fields of m, Z_δ, and D at section III did not affect the main result: the latitudinal profiles of m, Z_δ, and D agree and represent all the dynamic factors affecting their formation. Thus, we have found that different transparency characteristics of surface ocean water are related to each other and to the surface water circulation.

Let us check Eq. (4) in a different way. Determine the depth of white disk visibility $\tilde{Z}_\delta$ from the known experimental data on m [Ref. 8] by Eq. (4) and compare the results with the independent experimental measurements of Z_δ [Ref. 1]. Figures 2b and c show the regression dependences $m(\tilde{m})$ and $Z_\delta(\tilde{Z}_\delta)$, where the values of $\tilde{m}$ and $\tilde{Z}_\delta$ are obtained as described above from the data on m and Z_δ for sections I–III. Due to the regularities discussed above, the correlation coefficients for these parameters are rather high: $r_{m\tilde{m}}$ = 0.9, $r_{Z_\delta \tilde{Z}_\delta}$ = 0.8.

Thus, the above analysis of the experimental data has shown close correlation between m and Z_δ. This correlation is well described by Eq. (4) within the considered range of variability of the parameters studied. In the 5th research mission of *Dmitrii Mendeleev* Research Vessel in 1971, simultaneous field measurements of $K_{d_{500}}$ (and, consequently, m) and Z_δ were conducted in the zone with extremely transparent water (near Cook Islands). At m = 1.15 the white disk was visible at the depth of 66 m (Fig. 3).

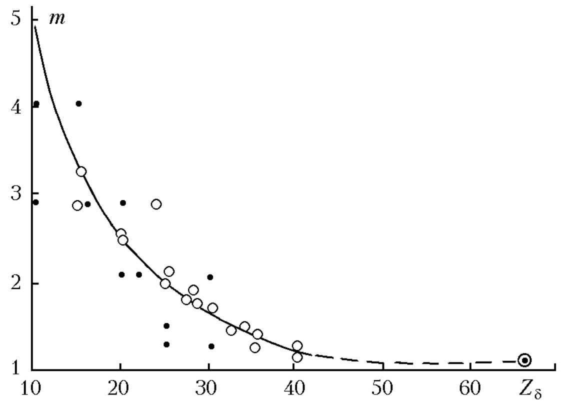

Fig. 3. Water type index m [Ref. 8] vs. the depth of white disk visibility Z_δ [Ref. 1] according to the experimental data: measurements (○); multiply coinciding measurements (•); measurements in extremely transparent waters of the Pacific Ocean near Cook Islands (⊙); calculation by Eq. (5) (——); interpolated data (– – –).

Such high values of Z_δ are unique in the practice of hydrooptical measurements. In Fig. 3, in the range

Z_δ = 40–70 m, the dashed line shows the interpolation between the value Z_δ = 40 m obtained by Eq. (4) and this experimental point with the maximum value Z_δ = 66 m. Figure 3 can be used for interpretation of remote measurements of m to determine Z_δ or, to the contrary, for estimation of m from Z_δ.

Thus, having analyzed the experimental data, we obtained the following results.

1. The semiempirical dependence was obtained between the depth of white disk visibility Z_δ and the optical index of water type m for the Atlantic Ocean; this dependence can be used for practical needs.

2. It was shown that the distribution (field) of Z_δ and m is formed under the effect of ocean currents, especially, zones of anticyclone or cyclone circulation, copying the structure features of these zones. The value of Z_δ stably correlates (while m anticorrelates) with the main characteristic of the surface water circulation, namely, the dynamic depth D (in m) at the 100 m level.

3. The possibility of using remote (even satellite) measurements not only to judge on the water cleanness in one or another ocean area, but also to detect convergence and divergence, upwelling and downwelling zones in the ocean was demonstrated.

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