Relation between the seawater optical characteristics and circulation of the Atlantic surface waters

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We have analyzed based on the experimental and theoretical data the distributions of the optical and circulation characteristics of the surface waters of the Atlantic Ocean. It was established that structures of the optical index of water type m are formed under the effect of dynamic factors; namely, they are closely connected with the ocean currents and large-scale cyclonic and anticyclonic structures. The structure features of distributions for the optical index of the water type m, field of surface ocean currents, and the dynamic height D at the 100-m depth level turned out to be similar for the whole Atlantic. Therefore, it is possible to derive a simple empirical equation for the $m(D)$ function.

The dependence of optical characteristics of seawater on hydrodynamic characteristics, such as currents, eddies, upwelling, and others, was observed for a long time (see, for example, Refs. 1 and 2). In this paper, using the Atlantic Ocean as an example, we compare the maps of surface currents and optical characteristics of the surface water. The optical properties are characterized by, possibly, the main optical characteristic of the water, namely, by the extinction of the solar flux as a function of depth.

Compare two maps: the map of Atlantic surface currents, borrowed from *the Atlas of Oceans*,[3] and the map of distribution of the optical index of water type m, which is directly connected with the coefficient of solar radiation extinction at λ = 500 nm, that is, in the central part of the visible spectrum of the solar radiation.[4,5] Remind that the optical index of water type is defined as $m = 43.43 \cdot Kd_{500}$, where Kd_{500} is the vertical extinction coefficient for the solar radiation at λ = 500 nm (Ref. 6). The index m has the following physical meaning. If z_{10} is the depth, at which the downward flux of the solar radiation at the wavelength λ = 500 nm is attenuated by 10 times, then the following simple equation is valid:

$$z_{10} = 100/m, \text{ m}, \qquad (1)$$

that is, if some water is characterized by this index, for example, $m = 3.3$ (as for some coastal regions of the Black Sea), then at the depth of 30 m the light at λ = 500 nm is attenuated by 10 times. Sometimes $2z_{10}$, at which the light is attenuated by two orders of magnitude, is used to estimate the thickness of the layer active in photosynthesis.

The superposition of these maps is shown in Fig. 1, where the arrows indicate the direction of surface currents, and isolines mark the approximate boundaries of water masses with the values of the optical index given in the figure caption.

The smallest value m = 1.15 ever observed in the World Ocean was found in the central regions of the Pacific Ocean near the Cook Islands[7]; the smallest values for the Atlantic Ocean, m = 1.2, were observed in the center of anticyclonic circulation of the Sargasso Sea.[7] The highest value for the Atlantic, m = 25–30 and higher, were observed to the north of Iceland, between the Island of Iceland and Jan Mayen Island, in the zone of cyclonic circulation caused by a branch of the East Greenland Current.[4]

Let us analyze this combined map (Fig. 1). First of all, it should be noted that the water between 40°N and 40°S forms a wide zone of typical clear ocean water with $1.5 \le m \le 2.1$ with some inclusions of clearer water at the centers of anticyclonic circulation both to the north and to the south of the equator. This vast zone is bounded by the system of currents: Gulf Stream to the north of the equator (↗), southern branch of the North Atlantic Current (→), Canaries Current (↙), and the North Trade Current (←). The arrows here indicate the prevailing direction of the corresponding currents. This system of currents forms the general anticyclonic circulation of water, which causes the observed cleanness of water. At the center of this circulation, in the Sargasso Sea, where the convergence is especially high, extremely clear water with $1.2 \le m < 1.5$ is observed. Near the eastern boundary of this vast zone the circulation pattern alternates. Due to the Coriolis force, the water of the Canaries Current tend to move away from the African coast, the currents diverge, and, as a result, powerful upwelling arises, in which m achieves values lying in the 4th, 5th, and 6th grades (see Fig. 1).

The similar general pattern is observed in the Southern Hemisphere. The system of currents: Brazil Current (↓), West Wind Current (→), Benguela Current (↑), and the South Trade Current (←) also form the anticyclonic circulation (see Fig. 1). The sharp turn of the southern branch of the South Trade Current, going into the Brazil Current, leads to the drastic increase of the anticyclonic circulation, that is, convergence, downwelling, and decrease of the optical water type index m to the values corresponding to the 1st and 2nd grades. To the contrary, in the eastern

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part of the southern Atlantic, the effect of the Benguela Current is marked. This current pushes the water off from the coast of South Africa and gives rise to upwelling – an analog of the Canaries Upwelling in the Northern Hemisphere. In divergence zones, in upwelling nutrient-rich waters, the sharp increase of organic matter is observed as a result of phytoplankton vital activity.

Between these two vast zones of typical ocean water of the Northern and Southern Hemispheres, at the equator, the supply of phytoplankton with nutrients also increases as a result of the well-known equatorial divergence of the currents and the upwelling arising in a narrow band. This process is accompanied by the increase of the phytoplankton concentration and the optical index, achieving the 4th grade: $2.1 \le m < 2.9$ (see Fig. 1).

Consider now the North Atlantic at the higher latitudes. To the north from 40°N, the pattern of the currents changes as compared to that considered above. In the northern part of the Atlantic Ocean, the isolines of m are elongated from the southwest to the northeast, what corresponds to the currents prevailing there. The main jet of the North Atlantic Current (↗), Irminger Current (←), East Greenland Current, and Labrador Current (↓), as well as Gulf Stream (→) form the cyclonic-type circulation of water. As a consequence, the divergence and upwelling arise, which lead to the increase in the amount of phytoplankton. The optical index m increases sharply, approaching the 4th, 5th, and 6th grades (see Fig. 1). The surface waters of the Northern Atlantic above 40°N are formed just in this way.

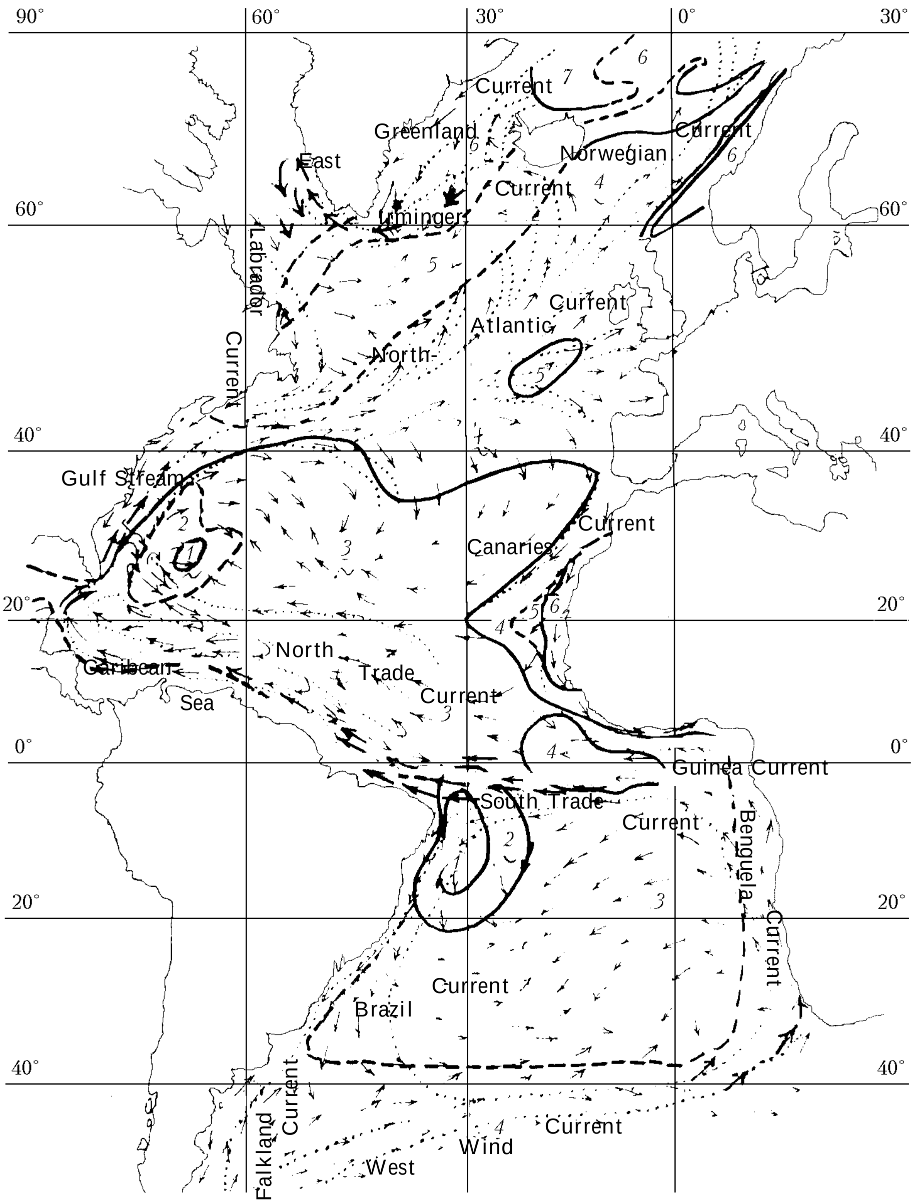

Fig. 1. Distribution of the optical index of water type in the Atlantic Ocean (isolines): $1.15 \le m < 1.3$ (*1*); $1.3 \le m < 1.5$ (*2*); $1.5 \le m < 2.1$ (*3*); $2.1 \le m < 2.9$ (*4*); $2.9 \le m < 4.1$ (*5*); $4.1 \le m < 5.3$ (*6*); $m > 5.3$ (*7*); and position (dots) and directions (arrows) of the principal surface currents.

Consider how the characteristics of the transparency of surface ocean water, namely, the optical index m is related to another circulation characteristic – the dynamic height D (in conditional dynamic centimeters) at the level of 100 m (Ref. 3). *The Atlas of Oceans*[3] presents the field of D values at the conditional reference surface (depth) of 1500 m; the map shows the lines of dynamic heights (isodynams), and the arrows along these lines indicate the direction of currents at the depth of 100 m. The comparison of the fields of m [Refs. 4, 5] and D [Ref. 3] has shown their identical structure. To the north from 40°N, the isolines of the field of D, as well as those of the field of m, have the direction from the southwest to the northeast in accordance with the direction of the Gulf Stream and the North Atlantic Current. In the latitudinal zone between 40°N and 40°S, the closed areas of high D values are bounded by the system of currents. Inside these zones, small-scale areas of even higher D values, corresponding to the areas of more developed anticyclonic circulation, are observed.[3] The central coordinates of these areas in the field of D almost coincide with the central coordinates of the analogous formations in the field of m and in the field of surface currents.

Using the fields of m [Refs. 4, 5] and D [Ref. 3], we have compared these characteristics along the meridional sections on the surface of the Atlantic Ocean, including all characteristic structure features of the compared fields. Section I along the longitude l = 32.5°W crosses the Atlantic Ocean from the north to the south in the central part and encompasses the whole range of variability of m and D. Section II in the western part of the Atlantic Ocean (longitude l = = 67.5°W) crosses the closed areas in the fields of m and D in the Sargasso Sea, where the anticyclonic circulation is observed. Section III in the eastern part of the Atlantic Ocean passes along the meridian l = = 20°W from the north to the south, toward the Canaries Upwelling. Thus, these sections encompass all the characteristic features of the distributions of m and D.

Tables 1 and 2 and Fig. 2 present the latitudinal dependence of the optical index m and the dynamic height D at the depth level of 100 m along the meridional sections I–III. As can be seen from Fig. 1,

Table 1. Latitudinal dependence of the index *m* of the Atlantic surface water along the meridional sections I–III according to the data from Ref. 4: *l* = 32.5°W (I), *l* = 67.5°W (II), *l* = 20°W (III)

I		II		III	
65–61°N	4.1–5.3	42–39°N	2.1–2.9	55–45°N	2.1–2.9
61–50.5	2.9–4.1	39–37	1.5–2.1	45–42	2.9–4.1
50.5–36	2.1–2.9	37–30	1.3–1.5	42–38	2.1–2.9
36–21	1.5–2.1	30–25	1.1–1.3	38–26	1.5–2.1
21–18	1.5–2.1	25–20	1.3–1.5	26–22	2.1–2.9
18–0°N	1.5–2.1	20–15	1.5–2.1	22–20.5	2.9–4.1
0°N – 4°S	1.3–1.5	13°N	2.1–2.9	20.5–19	4.1–5.3
4–18°S	1.1–1.3			19–16	2.9–4.1
18–21.5	1.3–1.5			16–9	2.1–2.9
21.5–40°S	1.5–2.1			9–6	1.5–2.1
				6°N – 1.5°S	2.1–2.9
				1.5–42°S	1.5–2.1

Table 2. Circulation of the Atlantic water at the depth of 100 m (dynamic height *D* in conditional dynamic centimeters) along sections I–III according to the data from Ref. 3: *l* = 32.5°W (I), *l* = 67.5°W (II), *l* = 20°W (III)

I				II		III	
65°N	415	03°N	480	41.5°N	440	50.5°N	450
63	420	1.5°N–1.5°S	485	40.5	450	47.5	460
61.5	425	08	490	39	460	36.5	470
60	427	10	493	38	470	11	480
55	428	15	500	37	480	4°N–8°S	485
51	430	20	507	36	490	16	490
50	437	22	510	35	500	20	500
49	440	25–30	510	34	505	24	510
47.5	450	33	510	33	505	33	500
45	457	40	500	24.5	505	41	490
42	460	41	490	21	500	44	480
40	469	43	480	18.5	495	45°S	470
39	470	44	470	16	490		
35	477	45.5	460	13.5	485		
31.8	480	47	450	11.5	480		
30.8	485	48	440	10°N	480		
30	485.5	49	430				
25	485.3	50°S	472				
21	486.6						
20	480						
14°N	475						

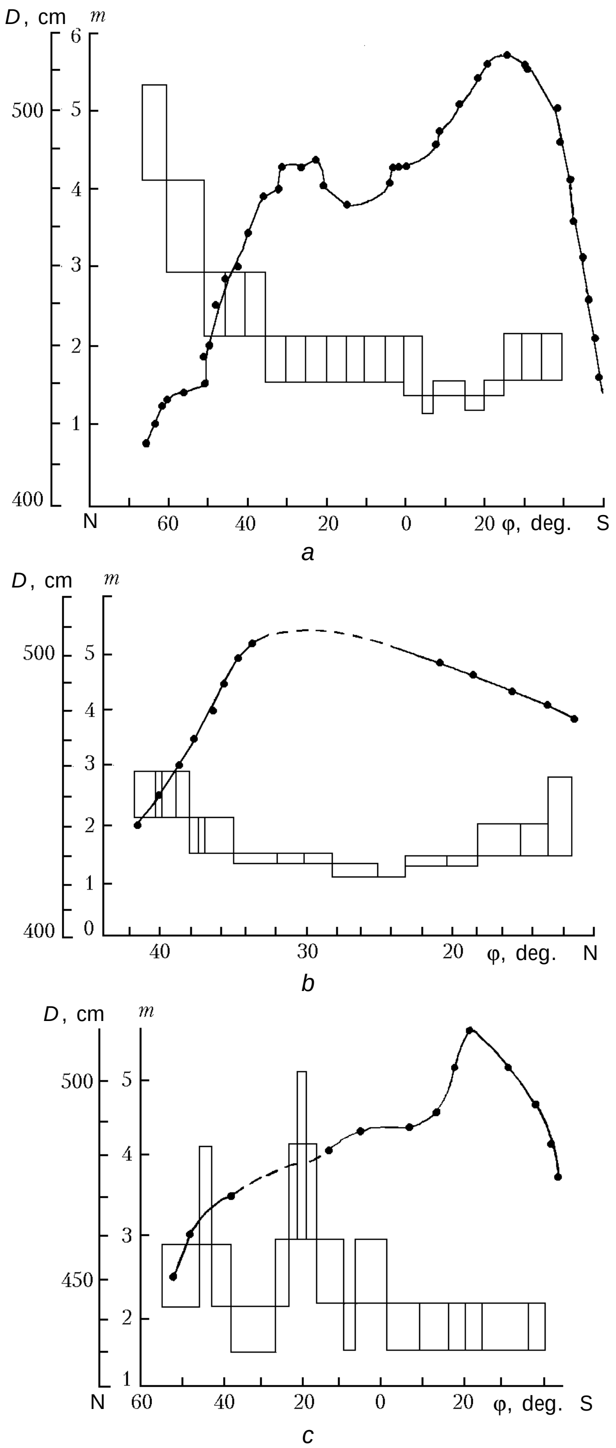

Fig. 2. Latitudinal dependence of the parameters of transparency of surface waters in the Atlantic Ocean (index *m*) according to the data of optical observations[4] and the circulation of ocean water (dynamic height *D* in conditional dynamic centimeters at the depth of 100 m) along the meridional sections I–III: *l* = 32.5°W (*a*); *l* = 67.5°W (*b*); *l* = 20°W (*c*).

section I crosses the central and southern branches of the North Atlantic Current in the latitudinal zone between 65 and 40°N. The index *m* decreases sharply from the north to the south (Table 1, Fig. 2*a*), that is, the water transparency increases drastically along this section.

The dynamic height *D* in this latitudinal belt at section I exhibits quite the opposite behavior: the value of *D* increases from the north to the south to 40°N (Table 2, Fig. 2*a*). In the latitudinal zone from 40°N to the equator, the index *m* remains practically unchanged and amounts to $1.5 \le m < 2.1$. In this latitudinal zone of transparent water, the dynamic height along section I varies insignificantly (see Table 2, Fig. 2*a*). To the south from the equator, when crossing the closed area of very transparent water, when the minimum of *m* is observed, the dynamic height increase sharply, achieving the maximum near 25°S. Farther, to 40°S, where the West Wind Current is observed, the index *m* increases somewhat, while the dynamic height, to the contrary, decreases (see Figs. 1 and 2*a*). Thus, the comparison of the values of *m* and *D* for section I shows that in the Atlantic Ocean the stable anticorrelation of this parameters is observed along the section in a wide range of their variations: the smaller the dynamic height at the level of 100 m, which characterizes the circulation, the less transparent is water (and, correspondingly, the higher is the index *m*), and *vice versa*.

The same stable relation of the parameters *m* and *D* is observed in the Sargasso Sea along section II (see Fig. 2*b*). Actually, the latitudinal dependences of *m* and *D* in the zone from 50 to 30° N are opposite. From Figs. 1 and 2, we can see that the boundary near $D \approx 460$ cm separates the clear "convergent" ocean water with $m \le 2.9$ and the more turbid, "divergent" water with $m > 2.9$. At section III, the variations of *m* and *D* demonstrate the same tendency. As can be seen from Figs. 1 and 2*c*, section III crosses small alternating inhomogeneities of water with different transparency and inhomogeneities in the field of the dynamic height. When crossing the Atlantic Current from north to south in the latitudinal belt between 50 and 30°N, the value of *m* mostly decreases, except for a small area, corresponding to the area of less transparent water with the maximum $2.9 \le m < 4.1$ near 43°N. Within the 30 to 10°N part of the section III, the Canaries Upwelling is observed, in which the value of *m* increases sharply, achieving the maximum $4.1 \le m < 5.3$ at the latitude of 19.5°N, and sharply decreases to the south down to 8°N to the values $1.5 \le m < 2.1$. Then the area of near-equatorial, less transparent water with the anticyclonic circulation, showing itself as a maximum of *m*, is observed. Farther to the south, to 40°S, in the section III we can see the area of transparent water, where the index *m* is constant, $1.5 \le m < 2.1$ (see Fig. 2*c*).

Note that no complete coincidence of the expected and actually observed results is possible in a detailed comparison of the latitudinal dependence of *m* and *D*, because the data are averaged, the measurements were conducted not synchronously, and at some parts of sections I–III the data are insufficient (dashed lines in Figs. 1, 2*b*,*c*). In spite of this, the obtained results of combined analysis of the fields are indicative of the stable relation between the index m and the circulation characteristic – dynamic height D at the level of 100 m. Figure 3 shows this relation for the whole set of data on sections I–III. As can be seen from Fig. 3, the index m decreases with the increase of the dynamic height. This dependence can be approximated by the following equation:

$$m = 1 + 75 / (D - 400). \quad (2)$$

This regression curve can be used to determine the dynamic height from measurements of the optical index m in the optical spectral region (curve in Fig. 3).

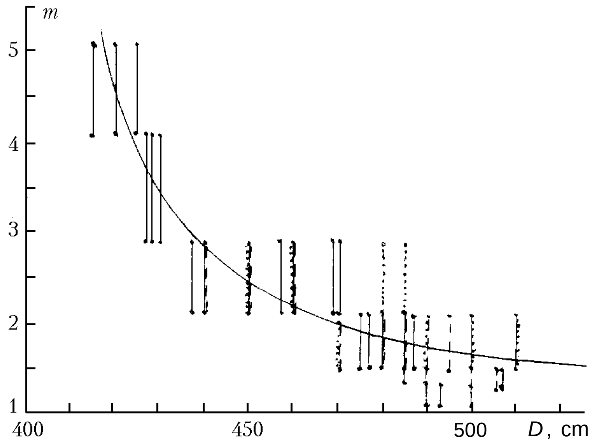

Fig. 3. Regression dependence of the index of surface water type m in the Atlantic Ocean on the dynamic height D at the depth of 100 m as judged from the data on sections I–III: ------ (section I); - - - - (section II); ……. (section III); solid curve shows the dependence $m(D)$ described by Eq. (2).

Thus, the combined analysis of the experimental and theoretical data on different characteristics of the ocean surface has yielded the following results:

1. It has been established that the optical properties of surface water in the open ocean are determined by the main currents of the Atlantic Ocean and the divergence (upwelling) and convergence (downwelling) zones created by them.

2. The characteristic structure features have been revealed in the distribution of the optical index m in the Atlantic Ocean, the field of the surface currents, and the field of the dynamic height D at the level of 100 m, and they turned out to be identical.

3. The anticorrelation has been found between the optical index m and the dynamic height D at the level of 100 m, which characterizes the circulation of water in the ocean. The equation approximating the dependence $m(D)$ has been derived.

4. As the value of m can be estimated from remote measurements of the ocean color, it becomes possible to determine the value of upwelling (downwelling) from satellite remote measurements.

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