The variability of transparency distribution in the upper layer of the Black Sea pelagial

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Variability of the extinction coefficient (EC) in the upper layer of deep part of the Black Sea in the period of stable optical state of sea waters (1978–1989) and of sharp decrease of their transparency (1990–1993) has been investigated with the use of a proposed set of typical EC values, reflecting the main features of its vertical distribution. In the second period, a 1.5-fold increase of EC was revealed in spring and 3-fold and more – in summer and fall in the surface layer, and about 1.5-fold – in the deep layer. To estimate the influence of water dynamics on the transparency distribution of typical EC values, their seasonal variations were analyzed in the main cyclonic and anticyclonic sea circulations.

Introduction

As is known, the seawater transparency is mainly determined by the content of suspended and dissolved organic matter, while their distribution depends on different hydrophysical, chemical, and biological processes.

Water optical structuring in the deep part of the Black Sea is influenced by weak water exchange between deep and surface layers, cold interlayer, sulfur zone, and stable cyclonic current system. An analysis of long-term field observation results has shown that the water transparency vertical structure in the Black Sea essentially differs from that in other seas.[1] As a result, four sufficiently stable optical layers were distinguished with certain hydrological, chemical, and biological characteristics. To describe optical properties of the layers, values of the extinction coefficient (EC), reflecting specific features of each layer, were suggested in Refs. 2 and 3.

Thus, EC at a zero depth and its mean value throughout the 0–25 m layer were chosen for the surface layer (0–60 m) in euphotic zone. To characterize the interlayer of the most transparent waters (60–130 m), EC at a depth of 100 m was chosen. To describe the deep turbid layer, EC amplitude in this layer and its depth were used. EC values at depths of 200 and 400 m characterized optical properties of the sea's hydrogen sulfide zone.

The choice of EC at a depth of 100 m for characterization of the transparent water layer is not quite reasonable, because of the dependence of its depth on a region of measurements. Thus, the transparent water depth equals to (80 ± 22) m in cyclonic circulations (upwelling zone) and (142 ± 28) m in anticyclonic circulations (downwelling zone). Besides, increased EC values, characterizing deep turbid layer, are sufficiently frequent in unpwelling zones at a depth of 100 m.

A minimal set of typical EC values, taking into account main features of its vertical distribution more accurately in comparison with the given above, includes[4]: the EC value ε_{10} at a depth of 10 m, where an influence of ships, destroying EC stratification, is diminished, as well as the influence of unavoidable sea pollution from ships; the EC minimum ε_{min} at its vertical profile in the layer of increased transparency; the EC maximum ε_{max} in the deep turbid layer; $Z_{\varepsilon_{min}}$ and $Z_{\varepsilon_{max}}$, being the depths of ε_{min} and ε_{max}, respectively; the mean EC ε_m in the layer from sea surface to the depth of ε_{min}.

Seasonal maps of the mean many annual EC values, were built by the observation results in 1977–1985 and analyzed.[3] A sharp decrease of water transparency at the end of 80th – beginning of 90th was described in Ref. 5 only by the results of measurements of the Secchi disk visibility depth.

The aim of this work is the analysis of inter-annual and seasonal variability of water transparency distribution in the upper layer of the deep part of the Black sea with the use of the above-suggested typical EC values, obtained at the Marine Hydrophysical Institute of NAS of Ukraine for 1978–1995 period. At all, 1600 observations were carried out (414 in spring, 365 in summer, and 821 in fall) in 24 expeditions. EC values were measured (at decimal base of logarithm and a wavelength of 420 nm) down to the 300-m horizon with sensing transparency meters.[6]

Results and discussion

Long-term observations of the Black sea water transparency, measured by the Secchi disk visibility depth, has shown that the optical state of the waters was quasistable to the middle of 80th. A sharp decrease of water transparency was observed at the end of 80th – beginning of 90th.[5] After 1992, water transparency began to increase and in 1998–2002 reached the annual-average values, observed in the second half of 80th (before its sharp decrease). This was also confirmed by EC values, measured in

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the surface (ε_{10}) and deep (ε_{max}) layers (Fig. 1) in period 1 (1978–1989) of quasistable optical state of seawaters and period 2 (1990–1993) of the sharp decrease of their transparency. EC measurement results in December, 1994 and April, 1995 witness of a pronounced tendency to EC values decrease (water transparency increase).

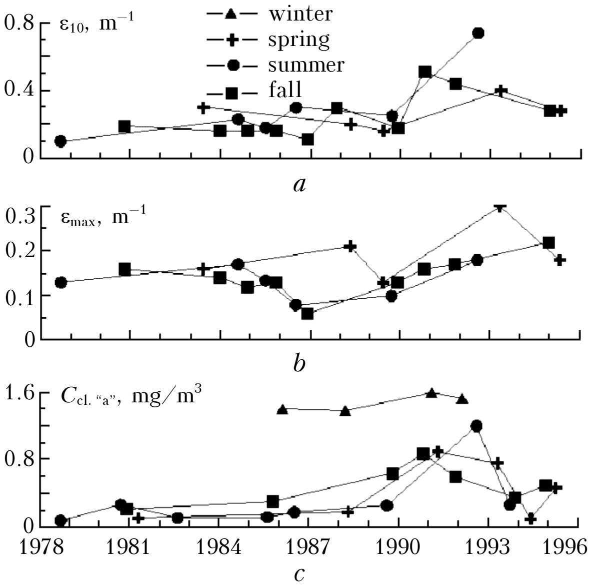

Fig. 1. Seasonal annual variations of EC in the surface (*a*) and deep (*b*) layers and chlorophyll "a" concentration in the surface layer (*c*) of the deep part of the Black Sea.

At the first stage of investigations, maps of EC distribution were built by observation data and their statistical estimates were calculated (mean value, standard deviation, and variation coefficient) for individual voyages and seasons.[7] Figure 2 exemplifies the EC distribution in the fall season (1978–1986). Table 1 presents the statistical estimates for EC in periods 1 and 2.

Table 1. Seasonal variations of mathematical expectation (M) and standard deviation (σ) of typical EC values in period 1 (1978–1989) and period 2 (1990–1993)

EC value	Season	M		σ	
		1	2	1	2
ε_{10}, m^{-1}	Spring	0.27	0.40	0.08	0.07
	Summer	0.22	0.74	0.10	0.25
	Fall	0.15	0.43	0.05	0.07
ε_{m}, m^{-1}	Spring	0.19	0.28	0.04	0.05
	Summer	0.16	0.30	0.06	0.08
	Fall	0.10	0.25	0.04	0.05
ε_{min}, m^{-1}	Spring	0.09	0.18	0.02	0.06
	Summer	0.07	0.10	0.03	0.05
	Fall	0.07	0.11	0.03	0.03
ε_{max}, m^{-1}	Spring	0.19	0.30	0.10	0.10
	Summer	0.13	0.18	0.07	0.08
	Fall	0.12	0.16	0.06	0.04
$Z_{\varepsilon_{min}}$, m	Spring	109	128	31	40
	Summer	104	114	26	36
	Fall	106	92	24	23
$Z_{\varepsilon_{max}}$, m	Spring	128	145	30	43
	Summer	124	130	25	35
	Fall	124	112	22	21

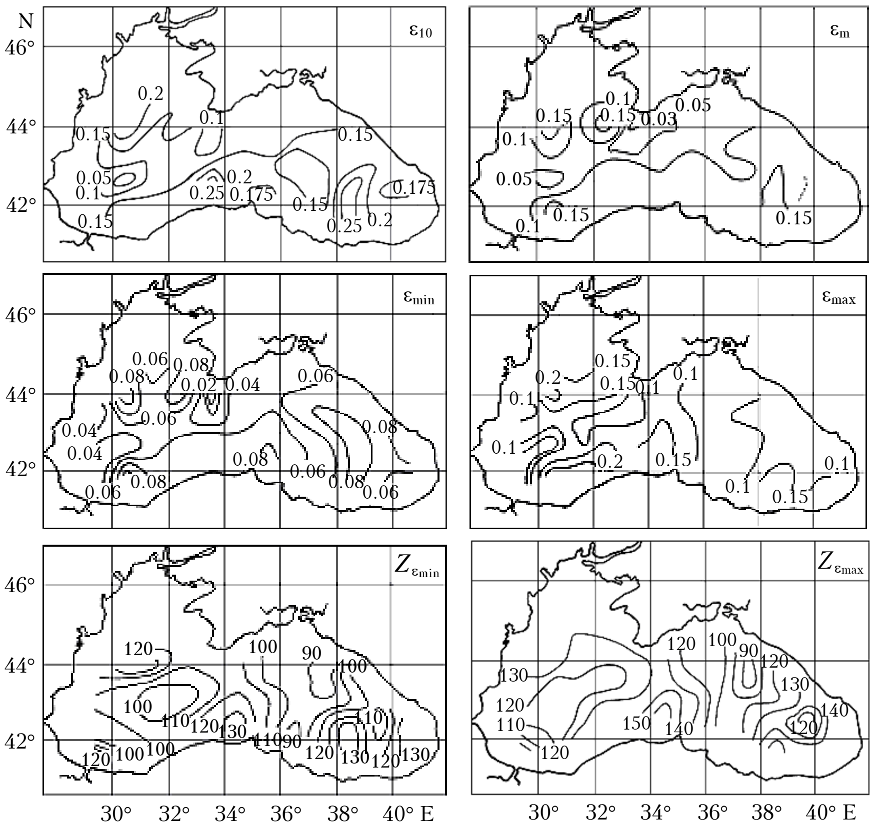

Fig. 2. Distribution of typical EC values in fall season in 1978–1986.

The analysis of data in Table 1 shows, that seasonal variations of EC values were mostly pronounced in period 1 in the surface layer. A decreased transparency in this layer was observed in spring; it increased to the end of the year (EC decreased). In deep layers (ε_{min}, ε_{max}), seasonal variations behaved similarly, but their values differed slightly in summer and fall. The depths of ε_{min} and ε_{max} varied insignificantly as well – from (104 ± 26) to (109 ± 31) m and from (124 ± 25) to (128 ± 30) m, respectively. Annual EC variations were noticeably pronounced in the surface and deep layers as well (see Fig. 1). Thus, in period 1, ε_{max} varied between 0.08 and 0.17 m^{-1} in summer and between 0.05 and 0.16 m^{-1} in fall.

Period 2 concurred with wide spread of *Mnemiopsis leidyi* in the sea. In this period, increased concentrations of chlorophyll "a" were observed (Fig. 1*c*). This was the evidence of an intense development of phytoplankton (especially of its fine-sized species[5]), which resulted in a noticeable decrease in transparency (see Fig. 1 and Table 1). Thus, EC in the surface layer increased 1.5-fold in spring, 3-fold and more in summer and fall, and about 1.5-fold – in these seasons in the deep layer. The transparency minimum in the surface layer was observed in summer, 1992 ($\varepsilon_{10} = 0.6$–1.1 m^{-1}); variation ranges of ε_{10} in spring and fall were close and equal to 0.35–0.6 m^{-1}. The character of seasonal variations of EC in deep layers was similar with those in period 1, but their depths differed: they were deeper in spring and closer to the sea surface in fall.

The analysis of the maps (Fig. 2) has shown the proximity of individual areas of decreased and increased EC values and depths of transparent and turbid layers with some known dynamic formations in the sea in both observation periods. This indirectly confirms the influence of water dynamics on the transparency distribution. Thus, it was noted in Ref. 4, that areas with minima of these parameters in central regions of western and eastern parts of the sea coincided with cyclonic circulations (CC) there. Sea areas with increased values of the parameters, mostly located in southern regions of the sea, coincided with convergence zones and anticyclonic circulations (ACC). The noted peculiarities of transparency distribution are well seen in Fig. 2.

At the second stage of investigations, the influence of water dynamics on the transparency distribution was studied in more detail. For each expedition, maps of dynamic topography of sea surface were built, where stable CC (western and eastern) and quasistable ACC ("Sevastopol", in the south-eastern part of the sea, along the Caucasian and Anatolian coasts) were identified with the used data on vertical structure of hydrological parameters. Statistical estimates of typical EC values in spring and fall periods were calculated by measurements at stations, which spatially coincided with the above dynamic formations (Table 2). The analysis of their variations has shown the following.

In period 1, the transparency in the surface layer in western CC slightly increased to the end of year (EC values decreased). Low seasonal variability of EC values, estimated by the variation coefficient in percents, was noted in spring (7–15%), while high one (30–50%) – in summer and fall. In period 2, the character of annual EC variations changed. The highest transparency of surface waters was observed in spring, while its anomalously low value – in summer (July, 1992). In this period, EC noticeably increased in all seasons (transparency decreased) as compared to period 1. Thus, on average, ε_{10} increased 2.4-fold in spring, 5.3-fold – in summer, and 3.8-fold – in fall, while its seasonal variability was low (7–12%) in all seasons.

EC maxima in deep transparent (ε_{min}) and turbid (ε_{max}) layers in both periods were observed in spring, as well as their relatively low seasonal variability (11–25%). In both periods, minimal EC values, approximately equal in each layer, were recorded in summer; their seasonal variability was high (36–57%). At the same time, these deep EC values in spring and fall were 1.4–2.0-times higher in period 2 than in period 1. Their depths also differed: in period 1, they increased for transparent and turbid layers from spring [(72 ± 4) and (97 ± 7) m, respectively] to the end of year [(87 ± 18) and (107 ± 11) m].

In period 2, the character of seasonal variations of the depths of these layers changed. Their maximal depths [(89 ± 15) and (97 ± 12) m] were observed in spring, and minimal ones [(56 ± 4) and (66 ± 3) m] – in summer, 1992; deep optical layers were at smaller depths than in period 1. A distance between the layers in period 2 was 8 m on average in spring and increased to 17 m to the end of year; in period 1, the distance was larger and equal to 20–25 m.

Absolute EC values and the character of their variations in the surface and deep layers in eastern CC differed insignificantly from similar characteristics in western CC in both periods. The EC in the surface layer in period 2 was noticeably higher (transparency lower) than in period 1. Thus, ε_{10} decreased 1.9-fold on average in spring, 4.6-fold – in summer, and 3-fold – in the fall; its seasonal variability also increased and was equal to 12–30%. In the deep layer, EC values increased 1.1–1.8-fold in this period. The character of annual variability of ε_{min} and ε_{max} depths was similar in both CC and in both periods (these depths increased throughout a year in period 1 and decreased in period 2). In the same time, these layers in eastern CC were deeper. The distance between the layers was unvaried in all the seasons in period 1 and equal to 20 m; this distance increased to 23–31 m in period 2.

In "Sevastopol" ACC, the transparency in the upper layer was a little higher in summer than in spring and fall, while its variability was sufficiently high and similar (28–37%) in all seasons in period 1. In period 2, EC (ε_{10}) increased (by a factor of 1.7 in spring, 2.3 – in summer, and 3.5 – in fall) and its seasonal variability decreased (12–24%) in comparison with period 1. The character of seasonal variations also changed. The transparency was noticeably lower in summer and fall in comparison with spring. In period 1, a decreased transparency in the deep layer was recorded in spring, while it decreased similarly in summer and fall; its variability was lower (11–28%) as compared to the surface layer.

In period 2, ε_{min} and ε_{max} increased (by a factor of 2.4–2.7 in summer and 1.7–2.1 – in fall), while their seasonal variability slightly decreased on average (8–25%). The character of annual variations did not change in period 2. Mean values of the depths of these layers varied insignificantly throughout a year in period 1 (135–139 m for the transparent layers and 152–163 m for the turbid ones). In period 2, the depths of the layers increased by 37 m on average in spring and decreased by 19 m in summer and fall. The distance between the layers was maximal in spring and equal to 28–29 m on average in both periods. Minimal distances were recorded in period 1 in summer (13 m) and in period 2 in fall (16 m).

In ACC in the south-eastern part of the sea, absolute EC values in the surface and deep layers and their seasonal variability were slightly higher than those in "Sevastopol" ACC, and the character of seasonal variations was the same (EC decreased to the end of year). In period 2, EC in the surface layer increased (by a factor of 1.3 in summer and 2.1 – in fall), while its seasonal variability decreased (by 6–17%) in comparison with period 1, when it was equal to 27–48%. The water transparency was virtually invariable in the deep layer in period 2. EC values (ε_{min} and ε_{max}) were lower than in "Sevastopol" ACC, while the character of their seasonal variations (EC increase to the end of year) was the same in both circulations. The depths of the transparent and turbid layers and their seasonal variations were close for both circulations in period 1. In period 2, the depths decreased in fall, like in "Sevastopol" ACC, and noticeable increased in summer (by 25–29 m). The difference in distances between the layers differed insignificantly in both periods (10–14 m in summer and 15–16 m in fall).

Table 2. Seasonal variations of mathematical expectation (*M*) and standard deviation (σ) of typical EC values in different dynamic formations in periods 1 (1978–1989) and 2 (1990–1993)

EC value	Season	Variable	WCC		ECC		ACC NW		ACC SE	
			1	2	1	2	1	2	1	2
ε_{10}, m^{-1}	Spring	*M*	0.17	0.41	0.21	0.39	0.24	0.40	0.26	–
		σ	0.02	0.05	0.05	0.05	0.09	0.05	0.05	–
	Summer	*M*	0.17	0.90	0.19	0.88	0.28	0.65	0.27	0.36
		σ	0.09	0.06	0.08	0.26	0.09	0.10	0.13	0.06
	Fall	*M*	0.12	0.45	0.14	0.42	0.18	0.63	0.22	0.46
		σ	0.04	0.04	0.03	0.05	0.05	0.15	0.06	0.03
ε_m, m^{-1}	Spring	*M*	0.14	0.32	0.16	0.25	0.16	0.30	0.22	–
		σ	0.01	0.04	0.02	0.05	0.05	0.03	0.04	–
	Summer	*M*	0.16	0.45	0.16	0.32	0.13	0.31	0.13	0.17
		σ	0.05	0.05	0.07	0.09	0.04	0.03	0.04	0.01
	Fall	*M*	0.10	0.45	0.11	0.42	0.12	0.26	0.15	0.46
		σ	0.05	0.04	0.04	0.05	0.02	0.05	0.03	0.03
ε_{min}, m^{-1}	Spring	*M*	0.09	0.18	0.09	0.15	0.09	0.22	0.09	–
		σ	0.01	0.03	0.01	0.05	0.01	0.05	0.01	–
	Summer	*M*	0.06	0.07	0.09	0.06	0.07	0.12	0.07	0.07
		σ	0.03	0.04	0.06	0.02	0.02	0.03	0.03	0.03
	Fall	*M*	0.06	0.12	0.06	0.11	0.07	0.13	0.08	0.10
		σ	0.03	0.05	0.03	0.02	0.02	0.01	0.01	0.01
ε_{max}, m^{-1}	Spring	*M*	0.13	0.24	0.13	0.24	0.15	0.40	0.21	–
		σ	0.02	0.06	0.01	0.07	0.04	0.05	0.10	–
	Summer	*M*	0.12	0.11	0.11	0.12	0.13	0.22	0.13	0.14
		σ	0.05	0.04	0.07	0.02	0.03	0.05	0.04	0.03
	Fall	*M*	0.11	0.16	0.09	0.15	0.11	0.23	0.16	0.17
		σ	0.04	0.04	0.03	0.01	0.02	0.05	0.06	0.02
$Z_{\varepsilon_{min}}$, m	Spring	*M*	72	89	79	87	135	172	147	–
		σ	4	15	12	8	8	23	5	–
	Summer	*M*	79	56	90	77	139	120	152	181
		σ	5	4	10	21	11	20	25	28
	Fall	*M*	87	70	92	74	135	116	136	128
		σ	18	4	12	10	3	5	6	4
$Z_{\varepsilon_{max}}$, m	Spring	*M*	97	97	99	110	163	201	159	–
		σ	7	12	7	19	11	19	9	–
	Summer	*M*	99	66	110	108	152	140	166	191
		σ	9	3	10	25	6	17	27	27
	Fall	*M*	107	87	112	105	152	132	152	143
		σ	11	11	12	16	8	11	7	1

Note. Cyclonic circulations: WCC – western and ECC – eastern; anticyclonic circulations: ACC NW – "Sevastopol" and ACC SE – in the south-east part of the sea.

The analysis has shown that EC variations in cyclonic and anticyclonic circulations manifested themselves not always similarly. This is due to the influence of different hydrophysical, biological, and chemical processes on the transparency field formation in the Black Sea. A detailed study of this influence is of its own interest and will be a subject of further investigations. In this work, the noted differences can be explained in the following way.

In deep sea, non-affected by coast flowing, enriched with suspended matter, the transparency in the surface layer is mainly determined by the amount of phytoplankton and the products of its decay (detritus). Increased ε_{10} values in spring in the period of stable optical state of seawaters (period 1) are connected with winter phytoplankton "bloom" ($C_{\text{ch. "a"}}$ in Fig. 1*c* characterizes the content of living phytoplankton). In spring (after the "bloom"), the number of phytoplankton cells decreased due to their decay, while the amount of detritus, has not reached deep layers, increased. Hence, the total number of suspension particles was sufficiently large thus decreasing water transparency. As a rule, phytoplankton "bloom" was not observed in summer and fall. In period 2 of noticeably decreased transparency, the usual seasonal phytoplankton development cycle was destructed due to outbreak of fine-sized pyrophyte phytoplankton.[5] Its "bloom" was observed in summer (maximum was in 1992) and fall periods (see Fig. 1*c*).

Increased EC values (ε_{10}) in ACC in comparison with CC can well be due to the conditions of their formations. Quasistable ACC, including circulations, considered in this work, usually originates in a region between the shore zone and the Main Black Sea stream at its meandering; hence, turbid shoaling waters can get into the central parts of circulations.

The influence of water dynamics mostly manifests itself when considering the depths of transparent and turbid layers. Thus, water downwelling in ACC and their upwelling in CC are explained by higher depths of these layers in the former as compared to the latter. Different depth positions of these layers in circulations of the same type is connected with different intensities of circulations, determined by the orbital velocity of water masses at their periphery.

The influence of water dynamics on EC vertical structure is also confirmed by good agreement between seasonal variations of the depths of transparent and turbid layers and those of the lower boundary of cold interlayer and upper boundary of sulfur zone, respectively. This is also noted in the literature data.[1,8]

Conclusion

Using a set of typical EC values, suggested by the authors, which reflects the main features of its vertical distribution, the seasonal variability of EC has been investigated in the upper layer of the deep part of the Black Sea in period 1 (1978–1989) of quasistable optical state of seawaters and period 2 (1990–1993) of sharp decrease of their transparency. It has been revealed, that EC increased 1.5-fold in spring and 3-fold and more – in summer and fall in the surface layer, and about 1.5-fold – in the deep layer in period 2.

The influence of water dynamics on distribution of typical EC values has been considered. Seasonal variability of statistic estimates was analyzed for the EC values, determined in the regions of stable cyclonic (western and eastern) and quasistable anticyclonic ("Sevastopol" and in the south-east part of the sea) circulations.

It has been shown that the character of EC variations in CC and ACC is the same in both periods, while their values are higher in ACC. In period 1, EC decreased (transparency increased) in the surface and deep layers to the end of year. In period 2, EC maxima in the surface layer were recorded in summer and minima – in spring. In the deep layer, decreased EC values were obtained in summer. Absolute EC values were noticeably higher in period 2 than in period 1.

It has been ascertained that the transparent layer was deeper in ACC than in CC by (65 ± 5) m in period 1 and by (70 ± 17) m in period 2, and the turbid layer – by 50 m in period 1 and by 64 m in period 2. The distances between these layers in these circulations were similar on average and equal to 20–24 m.

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