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Parameters of the Light Volume Scattering Functions and Composition of Suspension in the Upwelling Zone at the Equator in the Indian Ocean

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Abstract
Purpose. The paper is aimed at presenting and discussing the results of measurements of the light volume scattering functions and their parameters, and also the suspension composition calculated from the light volume scattering functions in the upwelling zone at the equator in the western Indian Ocean.
Methods and Results. The measurement data of the light volume scattering function and the Secchi disk depth were obtained in the 10th cruise of the R/V *Akademik Vernadsky* in February, 1975. In the equator region, an oceanographic section was carried out along 54.5ºE from 2ºS up to 2ºN with the stations located in each 0.5º. The section data showed a water rise in this region. The following light scattering function parameters were calculated: the scattering and asymmetry coefficients, and the light volume scattering function elongation. Based on the light volume scattering functions, the following suspension parameters were calculated: mass and numerical concentrations of the organic and mineral particles, and average size of the organic particles. At the upwelling maximum at 0.4ºS, the scattering coefficient σ was 0.849 1/m, in the background waters at 2ºN – 0.207 1/m. Increase in the asymmetry coefficient of the light volume scattering function with the scattering coefficient is determined by relation $K = 255\sigma + 6$ (R = 0.97). The parameters of the light volume scattering functions and the suspension composition in the upwelling zones at the equator in the Indian and Atlantic oceans were compared; the results showed a higher concentration of small (mineral) suspended particles in the waters of the Atlantic Ocean. At the upwelling maximum, the mass concentration of total suspension C_{total} constituted 0.938 mg/l, and in the background waters – 0.364 mg/l.
Conclusions. The common value of angle θ_{max} at which the calculation of the total scattering coefficient using the scattering measurement in this direction is optimal for the Indian and Atlantic oceans is found to be 3.5º. The obtained relationship between the particle size of organic suspension and the suspension concentration in the upwelling zone confirms the previous studies, namely, productivity increase is accompanied by decrease of the particle sizes, and vice versa, in the low-productivity waters, the particle sizes increase. The bulk of the mass suspension concentration at the section consists of organic particles.

Keywords: scattering function, scattering coefficient, asymmetry coefficient, Secchi disk, organic suspension, mineral suspension, particle size

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Introduction

Light scattering by water and its impurities is characterized by a light volume scattering function (angular distribution of scattered light) depending on the wavelength and the scattering angle.

Information on the light volume scattering functions is necessary to solve numerous problems in hydrooptics: calculating the light fields in the sea, creating the underwater vision devices, developing the algorithms to determining the biooptical characteristics of ocean waters from the satellites etc. [1–5]. The light volume scattering functions permit to determine the concentrations both of the total suspension and its fractions – organic and mineral ones. Therefore, studying the light scattering in the waters of various regions of the World Ocean is an urgent task (papers [1] and [6–9]).

The data on the volume scattering functions resulted from measuring the spectral angular coefficient of light scattering in various water basins are few. Therefore, the information on the results of contact measurements of this quantity is of particular interest, and the data of such observations are important regardless of the time they were obtained.

The results of measuring the light volume scattering functions in the western part of the Indian Ocean are presented and discussed in the paper. The data were obtained in the 10th cruise of the R/V *Akademik Vernadsky* in February, 1975. An oceanographic section was made in the equator region along 54.5ºE from 2°S up to 2°N. The stations at the section were located in each 0.5°. At the section, a water rise was observed in the equator region. Up to 2019 these data were considered lost, that necessitates their coverage and publication.

During the expedition, the light volume scattering function and the Secchi disk depth were measured. The paper presents the results of measuring the volume scattering functions, their parameters, and the suspension composition calculated from the volume scattering functions in the upwelling zone at the equator in the western Indian Ocean.

Equipment and measurement technique

The light volume scattering function was measured by a nephelometer [2] (Table 1) at the depths from 5 to 105 m.

Table 1

Nephelometer specifications

Characteristic	Value
Measurement angles σ(Θ), º	2; 7.5; further through 5 till 162.5
Spectral range of measurements, nm	520 (± 40)
Measurement error σ(Θ), %	10
Maximum depth, m	150

The minimum angle, at which the light scattering coefficient is determined in the nephelometer, is 2°. The scattering coefficients at the angles θ (less than 2°) required for calculations, were obtained by extrapolating the measured volume scattering function to this range using the formula $\log\sigma(\theta) = A + B\theta + C\theta^2$. To obtain the coefficients A, B, C, the scattering coefficients σ(θ) measured at

[1] Kopelevich, O.V., Mashtakov, Y.L., Pavlov, V.M. and Ochakovsky, Y.V., 1974. [Light Scattering Properties of Seawater in Various Areas]. In: A. S. Monin and K. S. Shifrin, eds., 1974. [*Hydrophysical and Hydrooptical Research Works in the Atlantic and Pacific Oceans*]. Moscow: Nauka, pp. 113–116 (in Russian).

[2] Man’kovsky, V.I., 1981. [Marine Pulse Nephelometer]. In: B. N. Malinovsky, V. T. Cherepin, eds., 1981. [*Instruments for Scientific Research and Automation Systems in the Academy of Sciences of the Ukrainian Soviet Socialist Republic*]. Kiev: Naukova Dumka, pp. 87-89 (in Russian).

the angles θ (equal to 2; 7.5; 12.5°) were applied. At the angles exceeding 162.5°, σ(θ) = const was taken.

The Secchi disk depth was defined by the standard method.

Parameters of the light volume scattering function

Function of angular distribution of a scattering coefficient σ(θ) in the directions θ = 0–180° is used in hydrooptics as a characteristic of light scattering. In the theory of light scattering, function χ(θ) = 4πσ(θ)/σ, where σ is scattering coefficient, is called the light volume scattering function [3]. Function χ(θ) shows the probability of light scattering in different directions. In the present paper, the term "volume scattering function" is applied to function σ(θ), which indicates the amount of light scattered in different directions [6].

The following function parameters were calculated:

– scattering coefficient σ (м$^{-1}$): $\sigma = 2\pi \int_0^{180} \sigma(\theta)\sin\theta d\theta$;

–asymmetry coefficient: $K = \dfrac{\int_0^{90} \sigma(\theta)\sin\theta d\theta}{\int_{90}^{180} \sigma(\theta)\sin\theta d\theta}$;

– function elongation: $L(2;90) = \lg[\sigma(2)/\sigma(90)]$.

Formulas for calculating suspension

To calculate the suspension characteristics using the volume scattering functions, the formulas from paper [4] and [10] were used. The numerical and mass concentration of particles in water was calculated for three fractions with the particle radii *r* equal to 0.2÷0.5, 0.5÷1.0 μm and exceeding 1.0 μm. The particles with a radius within the ranges 0.2÷0.5 μm and 0.5÷1.0 μm constitute a mineral fraction of the suspension; those with a radius exceeding 1.0 μm – organic. While calculating the mass concentration, the density of mineral particles is assumed to equal 2 g·cm^{-3}, that of organic particles – 1 g·cm^{-3}.

To calculate the concentration of the particles with a radius *r* exceeding 1.0 μm, the scattering coefficient σ(θ) at the angle θ = 1° is used; for particles with a radius 0.2÷0.5 μm and 0.5÷1.0 μm – at the angles θ = 45° and θ = 6°. Table 2 represents the coefficients for calculating the number of particles *N* and their mass concentration *C* using the formula $N(C) = m \cdot \sigma(\theta) + n$ [11].

[3] Shifrin, K.S., 1951. *Light Scattering in a Turbid Environment*. Moscow, Leningrad: State publishing of technical and theoretical literature, 288 p. (in Russian).

[4] Kopelevich, O.V., Mashtakov, Yu.L. and Burenkov, V.I., 1975. [Investigating the Vertical Stratification of the Scattering Properties of the Sea Water by Means of the Submersible Small-Angle Scattering Meter]. In: L. M. Brekhovskikh and K. S. Shifrin, eds., 1975. *Hydrophysical and Optical Research in the Indian Ocean*. Moscow: Nauka, pp. 54-60 (in Russian).

T a b l e 2

Values of the regression coefficients *m*, *n* and rms relative errors δ in determining the suspension parameters

Radius of particles *r*, mn	Scattering angle θ, °	Number of particles *N*, mln/l			Mass concentration *C*, mg · m^{-3}		
		m	*n*	δ *N*	*m*	*n*	δ *C*
0.2–0.5	45	$3\cdot10^4$	–1.0	0.29	$8.9\cdot10^3$	–3.0	0.16
0.5–1.0	6	9.5	0.2	0.14	24.0	0.5	0.14
> 1.0	1	0.2	0.3	0.35	12.0	16.0	0.20

In [10] the following generalized formula is given to calculate the suspension characteristics ξ

$$\xi = A[B - \lg\frac{\sigma(\theta_1)}{\sigma(\theta_2)}]^P + C\lg[\frac{\sigma(\theta_1)}{\sigma(\theta_2)}] + D\,.$$

Based on the ratio lg[σ(0.5)/σ(2.0)], the average radius of organic particles r_{org} is determined. The coefficients *A, B, C, D, P* in the formula are found by means of a special table in [10].

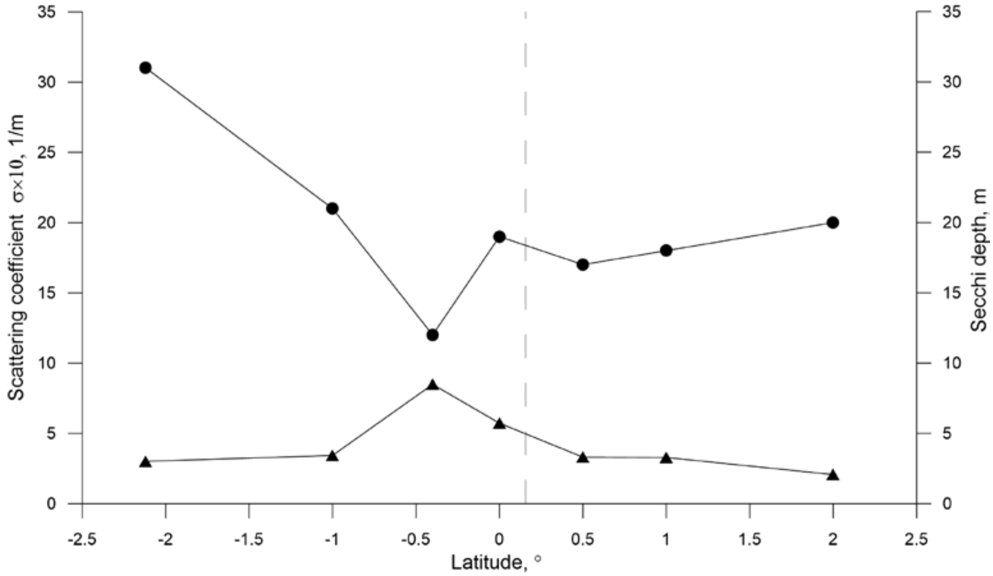
Results and discussion

Parameters of the light volume scattering functions. Fig. 1 shows the light scattering coefficient distribution at the 5 m depth and the Secchi disk depth at the section. At the upwelling maximum at 0.4°S, the scattering coefficient σ was 0.849 1/m, in the background waters at 2°N – 0.207 1/m. The parameters of the volume scattering functions at the section are presented in Table 3. Let us consider their variability.

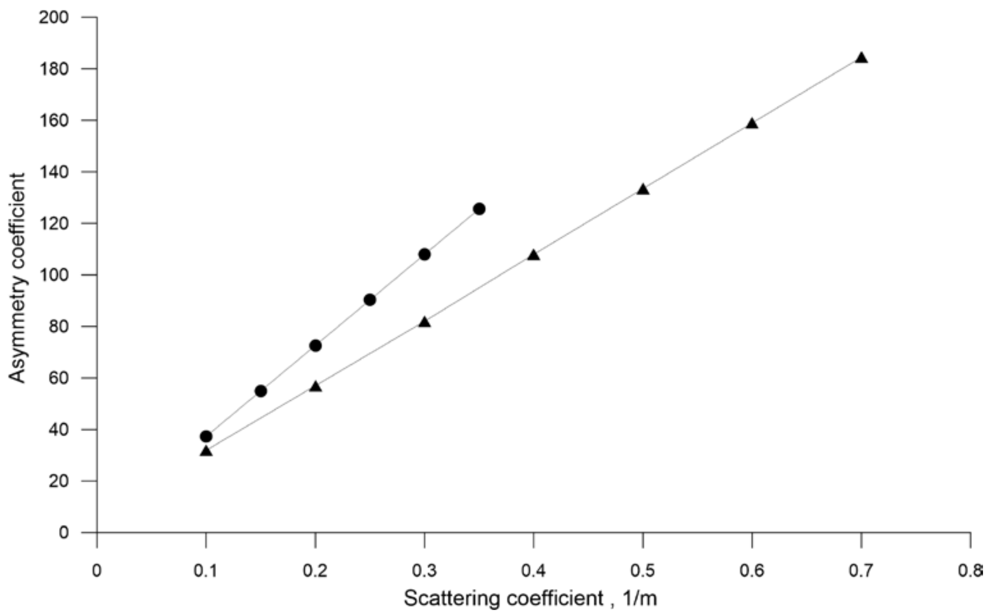
The data in Table 3 show an increase of the volume scattering function asymmetry coefficient with growth of the scattering coefficient. According to the data from [11], such a relationship is observed in all the natural waters, and it is of a regional character. In our case, the relationship $K = f(\sigma)$ is expressed by the formula ($R = 0.97$) $K = 255\sigma + 6$.

Based on the light volume scattering functions measured in the tropical zone of the Atlantic Ocean [6], the relationship $K = f(\sigma)$ was calculated for the upwelling waters at the equator (1ºS–2ºN; 20.5º–22.0ºW). Relationship formula is as following: ($R = 0.96$): $K = 353\sigma + 2$.

Fig. 2 shows relationships $K = f(\sigma)$ for the upwelling waters at the equator in the Indian and Atlantic oceans. The lower slope of the relation line $K = f(\sigma)$ for the Indian Ocean waters (according to [11]) indicates a higher concentration of small (mineral) suspended particles as compared to that in the Atlantic Ocean waters. This fact is confirmed by calculations of the suspension composition. The average ratio of the mineral particles concentration to the total suspension concentration in the Indian Ocean C_{min}/C_{total} is 0.17, whereas in the Atlantic Ocean – 0.06.



F i g. 1. Scattering coefficient at the 5 m depth (▲) and Secchi depth (●) at the section across the equator (indicated by a dashed line) along 54.5º E



F i g. 2. Relationship between the asymmetry and scattering coefficients in the upwelling zone at the equator in the Indian (▲) and Atlantic (●) oceans

The angular scattering coefficients σ(θ) are related to the general scattering coefficient σ (м$^{-1}$): $\sigma = 2\pi \int_0^{180} \sigma(\theta) \sin\theta d\theta$. Having found the relation formula σ = *f*[σ(θ)] for a certain angle, one can determine the scattering coefficient using the value of σ(θ) with no measurements of the whole light volume scattering function.

T a b l e 3

Parameters of the light volume scattering functions at different points of the section

Coordinates	Depth, m	Scattering coefficient σ, 1/m	Asymmetry coefficient	Elongation
02º 07′ S, 54º 31′ E	5	0.301	45.4	4.26
02º 07′ S, 54º 31′ E	42	0.274	43.2	4.19
02º 07′ S, 54º 31′ E	75	0.260	39.6	4.12
02º 07′ S, 54º 31′ E	105	0.239	37.0	4.12
01º 01′ S, 54º 29′ E	5	0.343	90.5	4.32
00º 26′ S, 54º 31′ E	5	0.849	163.0	4.55
00º 26′ S, 54º 31′ E	20	0.616	170.0	4.57
00º 26′ S, 54º 31′ E	57	0.308	99.5	4.41
00º 00′ N, 54º 26′ E	5	0.573	145.0	4.59
00º 29′ N, 54º 25′ E	5	0.331	94.0	4.45
01º 00′ N, 54º 37′ E	5	0.329	71.8	4.25
02º 00′ N, 54º 30′ E	5	0.207	55.7	4.32

The authors of papers [5] and [12–13] investigated the following problem: at what angle θ_{max}, the relationship σ = *f*[σ(θ)] is the closest. It was revealed that the values of this angle differ for different water basins and lie in the range 3–5º.

This problem was studied for the waters in the region of our interest. To determine θ_{max}, the correlation coefficient between σ(θ) and σ was calculated at different angles. The value of θ_{max} corresponds to the maximum correlation coefficient. Such an angle is found to be 3.5º. The relation equation for this angle is of the following form (R = 0.99)

$$\sigma = 0.041\sigma\,(3.5) + 0.096.$$

Similar calculations for the upwelling waters at the equator in the Atlantic Ocean yielded the same value of θ_{max} (3.5º). Relationship equation is the following (R = 0.98):

[5] Mankovsky, V.I., 1971. On the Relation between the Integral Light Scattering Coefficient of Sea Water and the Scattering Coefficient in a Fixed Direction. In: MHI, 1971. *Marine Hydrophysical Research*. Sevastopol: MHI. No. 6, pp. 145-154 (in Russian).

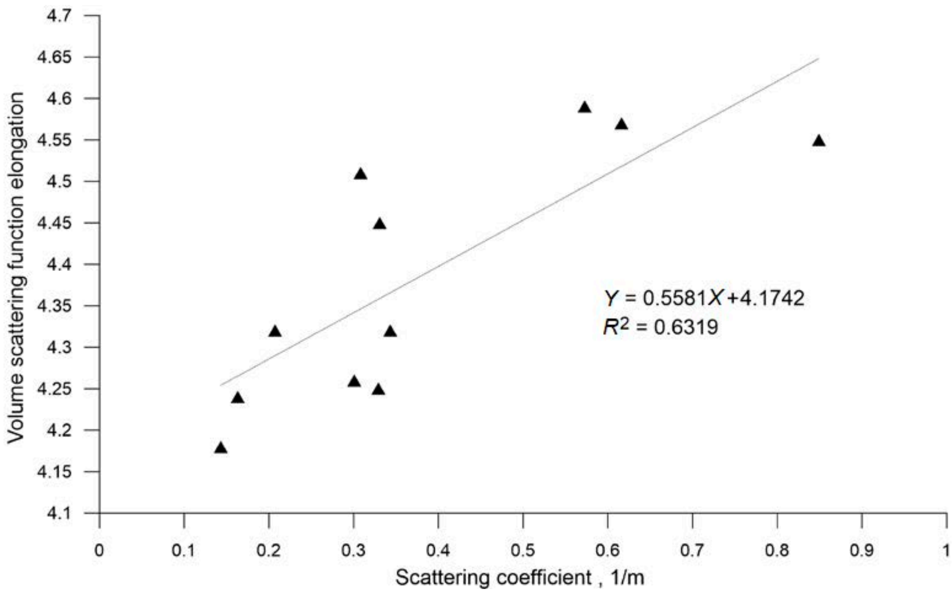
$$\sigma = 0.057\sigma\ (3.5) + 0.025.$$

Table 4 represents the values of angle θ_{max} in different water basins.

Table 4

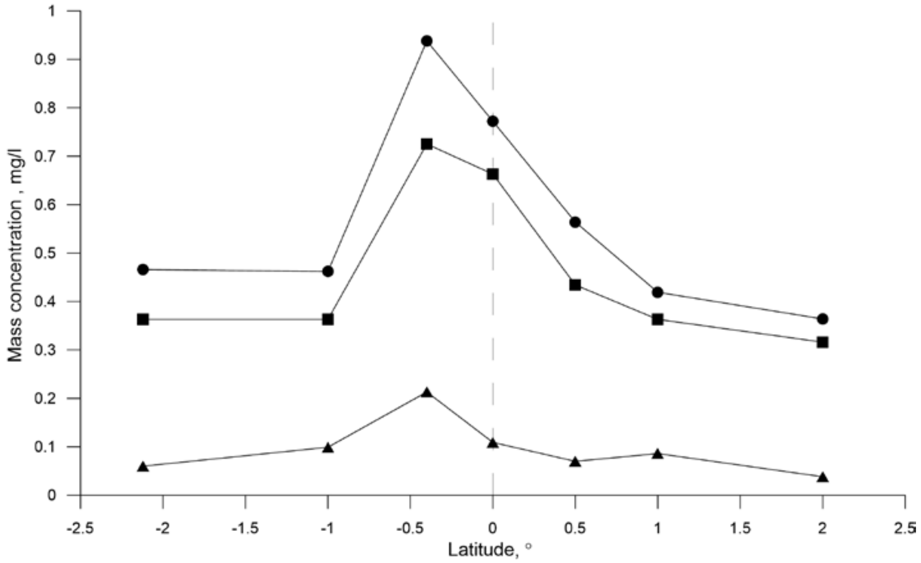
Values of the angle θ_{max}, at which the maximum value of correlation coefficient of the angle scattering coefficient with total scattering is observed

Region	θ_{max}, °	Correlation coefficient	Data source
Indian Ocean, upwelling zone at the equator	3.5	0.99	Present paper
Atlantic Ocean, upwelling zone at the equator	3.5	0.98	Present paper
Mediterranean Sea	3.5	0.98	[13]
Black Sea	5.0	0.97	Paper [5]

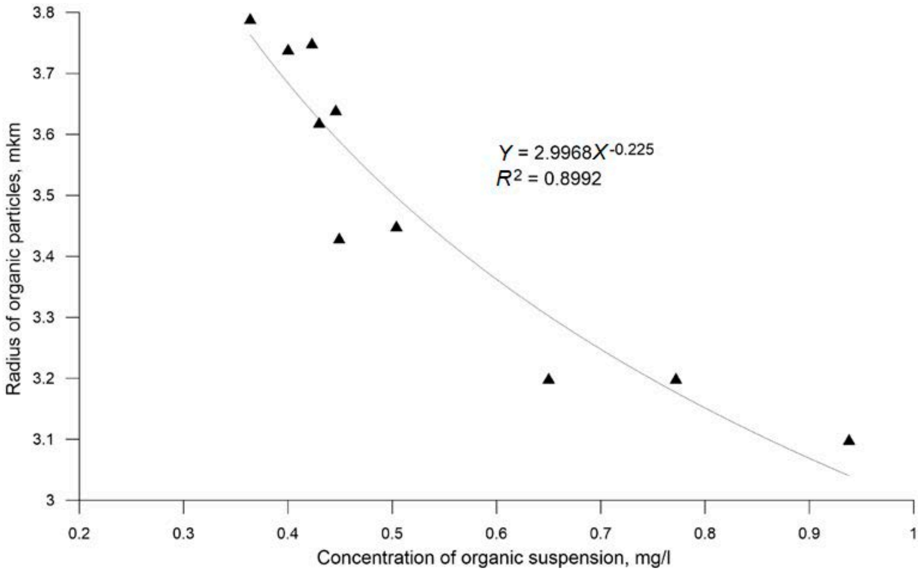


F i g. 3. Relationship between the light volume scattering function elongation and the scattering coefficient in the waters at the section across the equator

The relationships between the volume scattering function parameters in the region under study permit to note also the relationship between the volume scattering function elongation *L* (2;90) and the scattering coefficient σ (Fig. 3). It is seen from the figure that off the regression line, the points are considerably scattered, but on the whole, increase of the scattering coefficient is accompanied by growth of the volume scattering function elongation.



F i g. 4. Distribution of the suspension mass concentration at the section at the 5 m depth: mineral C_{min} (▲), organic C_{org} (■) and total C_{total} (●)



F i g. 5. Relationship between the average radius of organic particles r_{org} and the organic suspension concentration C_{org}

Suspension parameters. Based on the light volume scattering functions measured at the section, the following suspension parameters were calculated: mass (C) and numerical (N) concentrations of the organic and mineral particles and average size of the organic particles (r_{org}). The calculation results are presented in Table 5.

Fig. 4 shows the distribution of suspension mass concentration at the section at the 5 m depth. At the upwelling maximum at 0.4ºS, the suspension concentration C_{total} was 0.938 mg/l, and in the background waters at 2.00ºN–0.364 mg/l.

The bulk of the suspension mass concentration at the section consists of organic particles. The average ratio of the organic suspension concentration to that of the total suspension C_{org}/C_{total} is 0.83. According to [14], a similar parameter in the upwelling waters in the equator region (1ºS–2ºN; 20.5º–22.0ºW) in the tropical zone of the Atlantic Ocean was 0.94.

It was found in [15] that the sizes of organic particles in natural waters change depending on their productivity (trophicity, i.e., nutrient content): productivity increase is followed by decrease of the particle sizes, and vice versa, in the low-productive waters, the particle sizes increase. Such a relationship was also observed at the section in the Indian Ocean. Fig. 5 demonstrates the change of the average radius of organic particles depending on the suspension concentration.

Table 5

Suspension parameters at the section

Coordinates	Depth, m	C_{org}, mg/l	C_{min}, mg/l	C_{total}, mg/l	N_{org}, mln/l	N_{min}, mln/l	r_{org}, mn
02º 07′ S, 54º 31′ E	5	0.363	0.060	0.423	5.8	146	3.75
02º 07′ S, 54º 31′ E	42	0.371	0.075	0.446	6.2	190	3.64
02º 07′ S, 54º 31′ E	75	0.363	0.067	0.430	6.1	169	3.62
02º 07′ S, 54º 31′ E	105	0.326	0.074	0.400	5.5	185	3.74
01º 01′ S, 54º 29′ E	5	0.363	0.099	0.462	5.8	155	3.35
00º 26′ S, 54º 31′ E	5	0.725	0.213	0.938	12.1	345	3.10
00º 26′ S, 54º 31′ E	20	0.542	0.154	0.650	9.0	212	3.20
00º 26′ S, 54º 31′ E	57	0.496	0.045	0.541	4.0	77	3.72
00º 00′ N, 54º 26′ E	5	0.663	0.109	0.772	11.0	152	3.20
00º 29′ N, 54º 25′ E	5	0.434	0.070	0.504	7.3	129	3.45
01º 00′ N, 54º 37′ E	5	0.363	0.086	0.449	6.1	181	3.43
02º 00′ N, 54º 30′ E	5	0.316	0.038	0.364	6.2	83	3.79

It was shown in [15] that the size of organic particles changes due to a variation in the species composition of phytoplankton that, in its turn, is related to water productivity. In the eutrophic (high-productive) waters, the small-size species are predominant, while in the oligotrophic (low-productive) waters – the large-size ones.

Conclusion

The data on the parameters of the light volume scattering functions in the upwelling zone at the equator in the western part of the Indian Ocean are presented in the paper. At the maximum upwelling at 0.4º S, the scattering coefficient σ constituted 0.849 1/m. An increase of the volume scattering function asymmetry coefficient at growth of the scattering coefficient is determined by the relation $K = 255\sigma + 6$ (R = 0.97). This fact, having been compared to the similar relationship for the upwelling waters in the Atlantic Ocean has shown a lower slope of the relation line for the Indian Ocean. This fact, in its turn, indicates a higher concentration of small (mineral) suspended particles in water.

The value of the angle θ_{max} is defined equal to 3.5º, at which reconstruction of the total scattering coefficient by the scattering measurement in a given direction is optimal. The relation equation is $\sigma = 0.041\sigma\ (3.5) + 0.096$ ($R = 0.99$). The same value of θ_{max} (3.5º) was obtained for the upwelling waters at the equator in the Atlantic Ocean.

Based on the light volume scattering functions, the suspension concentration and its composition were calculated. At the upwelling maximum, the mass concentration of total suspension C_{total} was 0.938 mg/l, and in the background waters – 0.364 mg/l. The bulk of the mass suspension concentration at the section consists of organic particles. The obtained relationship between the particle size of organic suspension and the suspension concentration in the upwelling waters confirms the previous studies: productivity increase is accompanied by decrease of the particle sizes, and vice versa, in the low-productive waters, the particle sizes increase.

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The author has read and approved the final manuscript.
The author declares that he has no conflict of interest.