Original article

Characteristics of Suspended Matter in the South Ocean in the 20ºE Region Based on the Measurements of Light Volume Scattering Functions

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Abstract

Purpose. The purpose of the work is to present and discuss the results of determining the mass concentration of suspended matter and its organic and mineral fractions by measuring the light volume scattering functions in the South Ocean in the 20ºE meridian region from 37° to 55°S.

Methods and Results. The measurement data on the light volume scattering function were obtained in the 10th cruise of the R/V "Akademik Vernadsky" in January–February, 1975 at the oceanographic section along the 20ºE meridian from 37° to 55°S at the stations located 1º apart. The suspended matter composition was calculated based on the results of these measurements. The distribution of mass concentration of the suspended matter (total, organic and mineral) at the section was obtained. The maximum increase in the organic suspension concentration at the section was observed in the area of water rise at 53ºS: C_{org} = 0.830 mg/l (C_{total} = 1.062 mg/l), that indicates the highest water productivity in this region. Based on the empirical relationship with the organic suspension concentration, the chlorophyll concentration at the section was calculated. The relation between the total mass concentration of suspended matter and the scattering coefficient in surface waters in the form $C_{total} = 1.496\ \sigma_{520} - 0.0676$ (R = 0.95) was established. The features of the organic suspension vertical distribution in the areas of water rise and lowering, and with no signs of water vertical movement were considered.

Conclusions. Measurements of the light volume scattering functions in the South Ocean in the region of 20ºE and 37º–55ºS permitted to obtain the data on mass concentration of the total suspended matter, as well as its organic and mineral fractions. The maximum concentration of organic suspension is located in the vicinity of the average long-term position of the Polar Front, where the mass development of phytoplankton is observed regularly. The features of vertical structure of the suspension organic fraction are directly related to the water vertical dynamics. There is a close relationship between the mass concentration of total suspended matter and the scattering coefficient in the surface waters.

Keywords: light volume scattering function, suspended matter, organic suspended matter, mineral suspended matter, suspended matter concentration, South Ocean

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Introduction

Suspended matter plays an important role in many biological, physical, and geochemical processes occurring in ocean waters. In addition, suspended matter is

the most important factor affecting optical properties of ocean waters. Therefore, studying the concentration and composition of suspended matter in different regions of the World Ocean is an urgent task.

Suspended matter consists of organic and mineral particles. Organic suspension consists of living phytoplankton and detritus (fragments of dead phyto- and zooplankton). Mineral suspended matter mainly consists of particles of terrigenous origin.

Suspended matter affects the light scattering in the water. There are methods for inverting light volume scattering functions, which provide determination of the numerical and mass concentration of total suspension and its fractions, organic and mineral ones, from the measured light volume scattering functions $\sigma(\theta)$. One of these methods was applied in this work to determine suspended matter in the South Ocean waters.

The suspended matter composition was determined from the measurements of the light volume scattering functions at the oceanographic section along the 20°E meridian from 37° to 55°S during the 10th cruise of R/V *Akademik Vernadsky*. The measurements were performed in January – February 1975 in the "pre-optical satellite era". The specialized satellite systems for studying the ocean were absent in this period. This fact largely determines the interest in the presented data. The results of optical measurements in this expedition, light beam attenuation coefficients, and light volume scattering functions were published in [1]. The suspended matter characteristics presented in this paper complement the biooptical properties of waters in this region of the South Ocean.

The purpose of this work is to present and discuss the results of determining the mass concentration of total suspended matter and its organic and mineral fractions from the light volume scattering functions in the South Ocean waters in the region of 20°E meridian from 37° to 55°S.

Work area, equipment

The data were obtained in the 10th cruise of R/V *Akademik Vernadsky* (January – February 1975) in the South Ocean at a section along 20°E meridian from 37° to 55°S. The stations at the section were performed through one degree.

Light volume scattering functions $\sigma(\theta)$ were measured with a submersible nephelometer [1] at depths up to 200 m. The device measures $\sigma(\theta)$ at angles of 2º, then after 5º within the range of 7.5º…162.5º. The wavelength used is 520 ± 40 nm.

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 $\lg\sigma(\theta) = A + B\theta + C\theta^2$. To obtain the coefficients *A*, *B*, *C*, the scattering coefficients $\sigma(\theta)$ measured at angles θ equal to 2°; 7.5°; 12.5° were used. At the angles exceeding 162.5º, $\sigma(\theta)$ = const was taken.

[1] Mankovsky, V.I., 1981. [Marine Pulse Nephelometer]. In: B. N. Malinovsky and V. T. Cherepin, eds., 1981. [*Instruments for Scientific Research and Automation Systems in the Academy of Sciences of the Ukrainian SSR*]. Kyiv: Naukova Dumka, pp. 87-89 (in Russian).

Method for measuring light volume scattering function $\sigma(\theta)$

The functions were measured three times at each depth. The calculations were carried out using an averaged function.

The minimum depth at which the functions were measured was 5 m. This depth was due to the fact that measurements in most cases took place during waves, when, as a result of wave breaking, air bubbles appear in the upper layers of water, distorting light scattering by suspended matter.

Formulas for suspended matter calculation

To calculate the suspension characteristics from the light volume scattering functions, the formulas from the work [2] were used. This work provides formulas (λ_{scatt} = 549 nm) to determine the content of particles in water. The numerical and mass concentrations of particle are calculated for three suspended matter fractions with particle radii r = 0.2÷0.5 μm, r = 0.5÷1.0 μm, r > 1.0 μm. Particles with radii r = 0.2÷0.5 μm and r = 0.5÷1.0 μm constitute a mineral fraction of the suspended matter (small particles), with radii r > 1.0 μm – the organic fraction (large particles). When calculating the mass concentration, the density of mineral particles is taken equal to 2 g·cm^{-3}, the density of organic particles is 1 g·cm^{-3}.

To calculate the concentration of particles with radii r > 1.0 μm, the scattering coefficient $\sigma(\theta)$ at an angle θ equal to 1° is used, for particles with a radius r = 0.2÷0.5 μm and r = 0.5÷1.0 μm – at the angles of 45° and 6°, respectively. Table 1 represents the coefficients for calculating the mass concentration C (mg·m^{-3}) using the formula $C = m\sigma(\theta) + n$.

T a b l e 1

Values of the regression coefficients m and n and the root-mean-square relative errors δ of determining the suspension parameters

Particle radius r, μm	Scattering angle θ, °	m, mg·m^{-2}	n, mg·m^{-3}	δ C, mg·m^{-3}
0.2–0.5	45	$8.9 \cdot 10^3$	–3.0	0.16
0.5–1.0	6	24.0	0.5	0.14
> 1.0	1	12.0	16.0	0.20

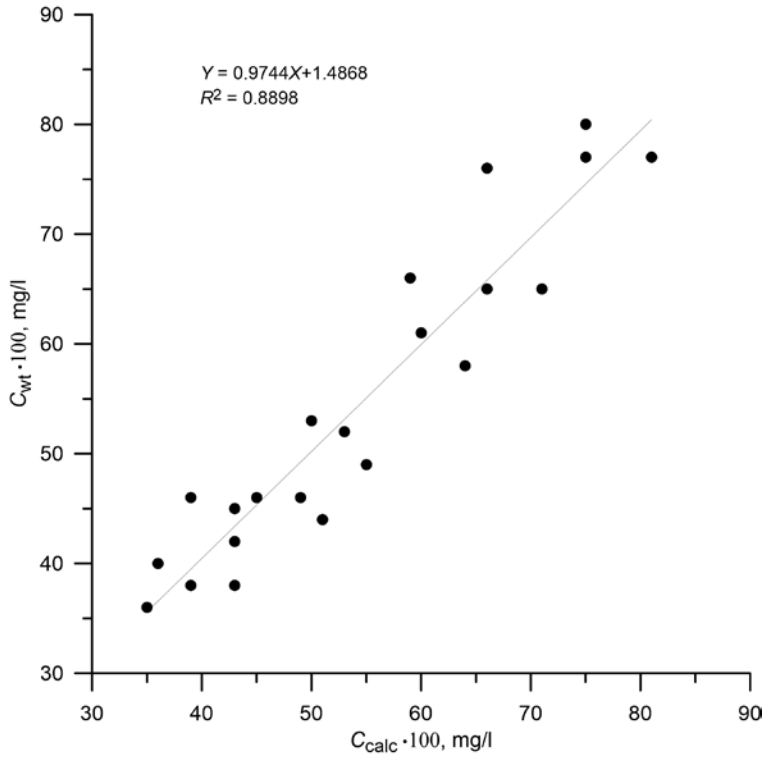
Verification of calculation formulas

The data from Table 1 for calculating the suspended matter were obtained in the work [2] when measuring the scattering coefficients at a wavelength λ = 546 nm. The effective wavelength for measurements of light scattering in the nephelometer applied in this work is 520 nm. In this regard, the calculation formulas were verified.

The suspended matter concentration was determined by the standard weight method in 22 water samples. In the same samples, the light volume scattering functions were measured. Fig. 1 shows a comparison of suspended matter concentrations determined by the weight method C_{wt} and calculated from the light scattering C_{calc}. Relationship is expressed by the formula: $C_{wt} = 0.97C_{calc} + 0.009$.

[2] Kopelevich, O.V., Mashtakov, Yu.A. and Burenkov, V.I., 1975. [Study of the Vertical Stratification of the Seawater Scattering Properties]. In: L. M. Brehovskih and K. S. Shifrin, eds., 1975. *Hydrophysical and Optical Studies in the Indian Ocean*. Moscow: Nauka, pp. 54-60 (in Russian).

Correlation coefficient is $R = 0.88$. In the concentration range of 0.35÷0.80 mg/l, the difference $\Delta C = C_{calc} - C_{wt}$ is 0.0015…0.015 mg/l. Due to the insignificant difference between C_{calc} and C_{wt}, no adjustment to the C_{calc} was implemented.



F i g. 1. Relation between the suspended matter concentration determined by the weighing method C_{wt} and the suspended matter concentration calculated from the measurements of light volume scattering C_{calc}

It should be noted that the ratio $C_{calc} > C_{wt}$ obtained in the experiment agrees with the theoretical and experimental data [3] on the spectral variability of light scattering by particles, according to which the scattering value varies inversely proportional to the wavelength of the scattered light $\sigma(\lambda) \sim (1/\lambda)^n$.

Results and their discussion

Bad weather conditions (stormy winds, heavy seas) prevented measurements of the light volume scattering functions at all stations of the section; they were performed only at 8 stations out of 19. The results of measurements at these stations are presented in the tables and figures below.

Table 2 presents the mass concentration of suspended matter (total, organic and mineral) at a depth of 5 m at different points of the section, as well as the concentration of chlorophyll C_{chl}.

[3] Kopelevich, O.V., 1983. [A Low-Parameter Model of the Sea Water Optical Properties]. In: O. V. Kopelevich, 1983. [*Ocean Optics. Physical Ocean Optics. Vol. 1*]. Moscow: Nauka, pp. 208-235 (in Russian).

Table 2

Concentration of suspended matter and chlorophyll in the South Ocean at the section along the 20º E meridian at the 5 m depth

Latitude, φ	Scattering coefficient at wavelength 520 nm σ_{520}, 1/m	Concentration			
		suspension, mg/l			chlorophyll C_{chl}, mg/m^3
		organic C_{org}	mineral C_{min}	total C_{total}	
37	0.396	0.305	0.153	0.458	0.16
38	0.432	0.295	0.199	0.494	0.16
39	0.421	0.406	0.175	0.581	0.22
41	0.722	0.436	0.279	0.715	0.24
44	0.299	0.372	0.080	0.452	0.16
47	0.294	0.348	0.068	0.416	0.19
53	0.681	0.830	0.232	1.062	0.71
55	0.515	0.292	0.199	0.491	0.14

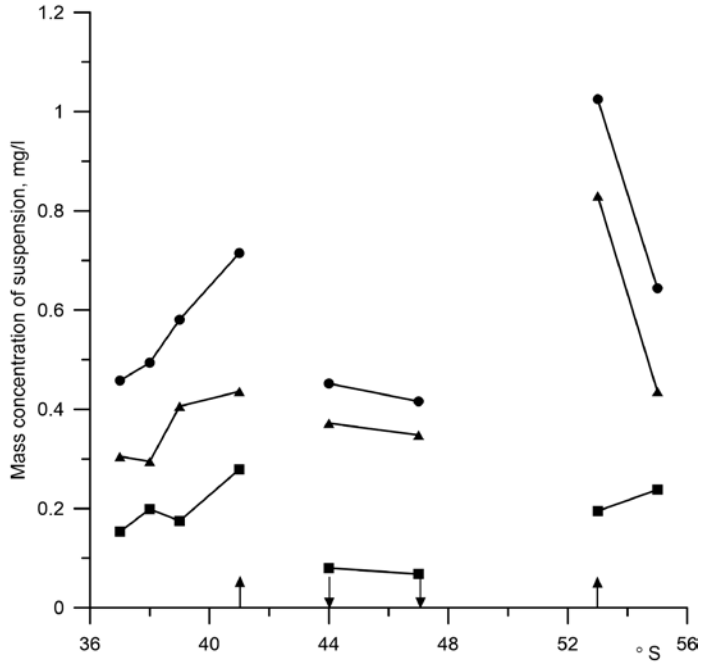
The concentration of chlorophyll C_{chl} (mg·m^{-3}) was calculated from the relationship with the concentration of organic suspended matter C_{org} (mg·l^{-1}). C_{org} was determined from the simultaneous measurements of these characteristics in the Atlantic Ocean during the 47th cruise of R/V *Mikhail Lomonosov*. The relationship equation is the following (R = 0.85): $\ln C_{chl} = 2.8\ (C_{org} - 0.95)$.

The suspended matter distribution in the section at a depth of 5 m is demonstrated in Fig. 2. In the figure the arrows indicate the areas of rise (at 41°, 53°S) and lowering (at 44°, 47°S) of waters, identified by hydrological features. In these areas, respectively, the increased and decreased concentrations of suspended matter and chlorophyll were observed.

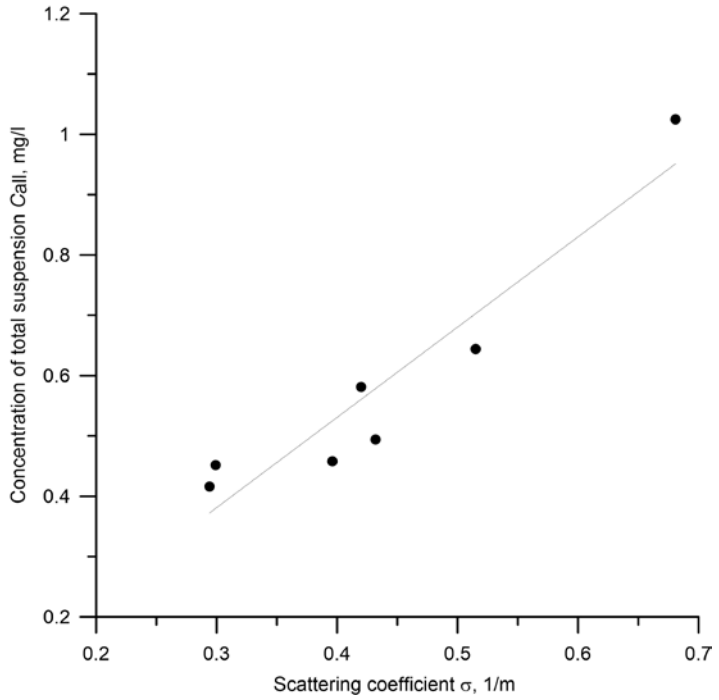
A particularly strong increase in the concentration of organic suspended matter was observed in the area of water rise at 53ºS: C_{org} = 0.830 mg/l (C_{total} = 1.062 mg/l). This indicates the highest water productivity at the section at 53ºS. This area is located in the vicinity of the average long-term position of the Polar Front, where mass development of phytoplankton is observed regularly [2–8] and is typical for this region of the South Ocean [9].

In Fig. 3 the comparison of the concentrations of the total suspended matter C_{total} (mg/l) with the scattering coefficients σ_{520} observed at the section along the 20°E meridian is shown. The relationship between these values (R = 0.946) is expressed by the formula $C_{total} = 1.496\ \sigma_{520} - 0.0676$.

The trophicity (nutritional value) of surface waters at the section was determined from chlorophyll concentration according to the classification from [10]. This classification was slightly expanded by us, and two subspecies in the mesotrophic waters were distinguished (Table 3).



F i g. 2. Distribution of mass concentration of organic (triangles), mineral (squares) and total (circles) suspension at the section along the 20° E meridian



F i g. 3. Relationship between the suspended matter mass concentration and the scattering coefficient at the section along the 20° E meridian

Table 3

Water types by chlorophyll [4] concentration

Water type	Chlorophyll concentration C_{chl}, mg·m^{-3}
Oligotrophic	< 0.1
Mesotrophic 1	0.1–0.5
Mesotrophic 2	0.5–1.0
Eutrophic	> 1.0

Table 4

Suspension concentration distribution with depth at 20° E in the areas with different vertical water dynamics

Depth, m	Suspended matter concentration, mg/l			Scattering coefficient, 1/m
	organic	mineral	total	
Water rise (*41° S*)				
5	0.436	0.279	0.715	0.722
25	0.725	0.307	1.032	0.853
Water rise (*53° S*)				
5	0.830	0.232	1.062	0.681
20	0.485	0.109	0.594	0.492
Water lowering (*44° S*)				
5	0.372	0.081	0.452	0.299
50	0.340	0.104	0.444	0.359
115	0.305	0.043	0.348	0.207
No signs of water vertical movement (*39° S*)				
5	0.406	0.175	0.581	0.421
25	0.356	0.154	0.510	0.414
50	0.348	0.133	0.481	0.359
55	0.312	0.041	0.353	0.189
162	0.262	0.022	0.284	0.129
No signs of water vertical movement (*55° S*)				
5	0.292	0.199	0.441	0.515
20	0.340	0.191	0.531	0.559
50	0.271	0.151	0.422	0.538
130	0.101	0.048	0.149	0.055

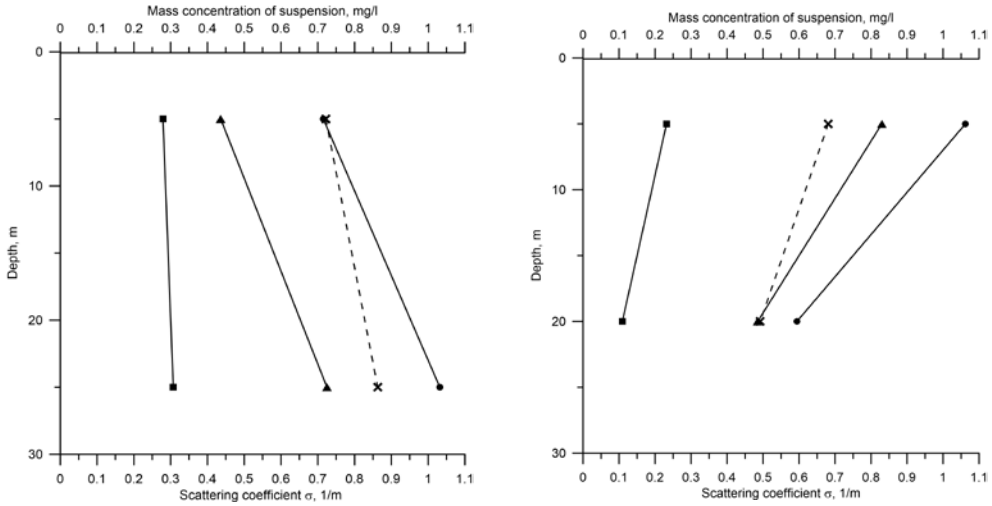
According to the classification (Table 4), at the section along the 20°E (see Table 3) all surface waters, except the waters at 53°S, belonged to the type “mesotrophic 1”, and at 53ºS – to the type “mesotrophic 2”.

In Table. 4 and in Fig. 4–6 the data on the vertical distribution of suspended matter concentration in the areas of rise and lowering of waters and with no signs of water vertical movement are presented. The organic fraction of the suspension is directly related to the dynamics of waters. Therefore, we will consider the features of the vertical structure of the suspension on its example.

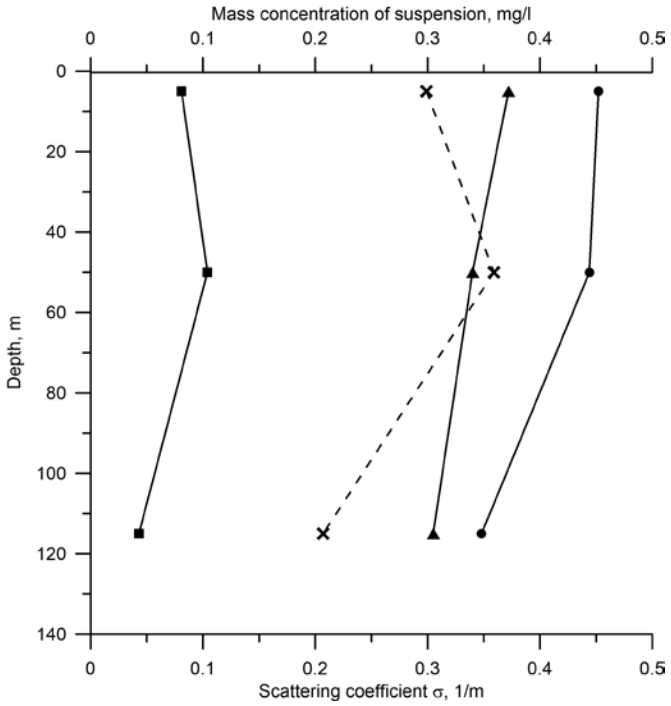
In the areas of water rise, nutrients are removed from the deep layers to the surface, which leads to an increase in the development of phytoplankton in

[4] Mankovsky, V.I. and Mankovskaya, E.V., 2022. Biooptical Characteristics on Macropoligon in the Northern Tropical Zone of the Atlantic Ocean and Their Relationship with Water Dynamics. *Oceanology*, 62(1), pp. 32-40. doi:10.31857/S0030157422010099 (in Russian).

these areas (an increase in the organic suspended matter concentration). Such a phenomenon was observed in the surface waters at 41° and 53° S (Fig. 4). In these areas the water rise was expressed by different ways depending on the distribution of hydrological characteristics (temperature, salinity, density).



F i g. 4. Depth distribution of the scattering coefficient (dashed line) and the mass concentration of organic (triangles), mineral (squares) and total (circles) suspended matter in the areas of water rise at 41°S (*left*) and 53°S (*right*)



F i g. 5. Depth distribution of the scattering coefficient (dashed line) and the mass concentration of organic (triangles), mineral (squares) and total (circles) suspended matter in the areas of water lowering at 44º S

At 41°S the water rise was expressed in an increase of organic suspension concentration C_{org} at a depth of 25 m, which amounted to 0.725 mg/l, compared with 0.436 mg/l at a depth of 5 m.

At 53°S the water rise was expressed in the surface layer, where at a depth of 5 m the organic suspension concentration amounted to C_{org} = 0.830 mg/l, and at a depth of 20 m C_{org} decreased to 0.485 mg/l.

In the water lowering areas the phytoplankton concentration in the surface layers is low due to a without of nutrients. It decreases with depth due to the death of cells and their gradual dissolution. Such a phenomenon was observed in the vertical distribution of organic suspended matter concentration at 44ºS (Fig. 5): at a depth of 5 m C_{org} is 0.372 mg/l, 50 m – 0.340 mg/l, 115 m – 0.305 mg/l.

The depth distribution of C_{org} in areas with no signs of water vertical movement (39° and 55°S) in both cases is characterized by a slight change in C_{org} with depth in the 50-meter surface layer (Fig. 6): at 39° S in 5–162 m layer C_{org} = 0.406…0.348 mg/l, at 55° S in the 5–130 m layer C_{org} = 0.340…0.271 mg/l. In the same regions, a uniform distribution of temperature and light beam attenuation coefficient was observed in the 50-meter surface water layer [1]. This is the so-called surface homogeneous layer, which is formed in the seas and oceans as a result of wind-wave mixing of waters. The “permanence” of the biomass in this layer is maintained by nutrients formed as a result of the partial decomposition of dead phytoplankton cells.

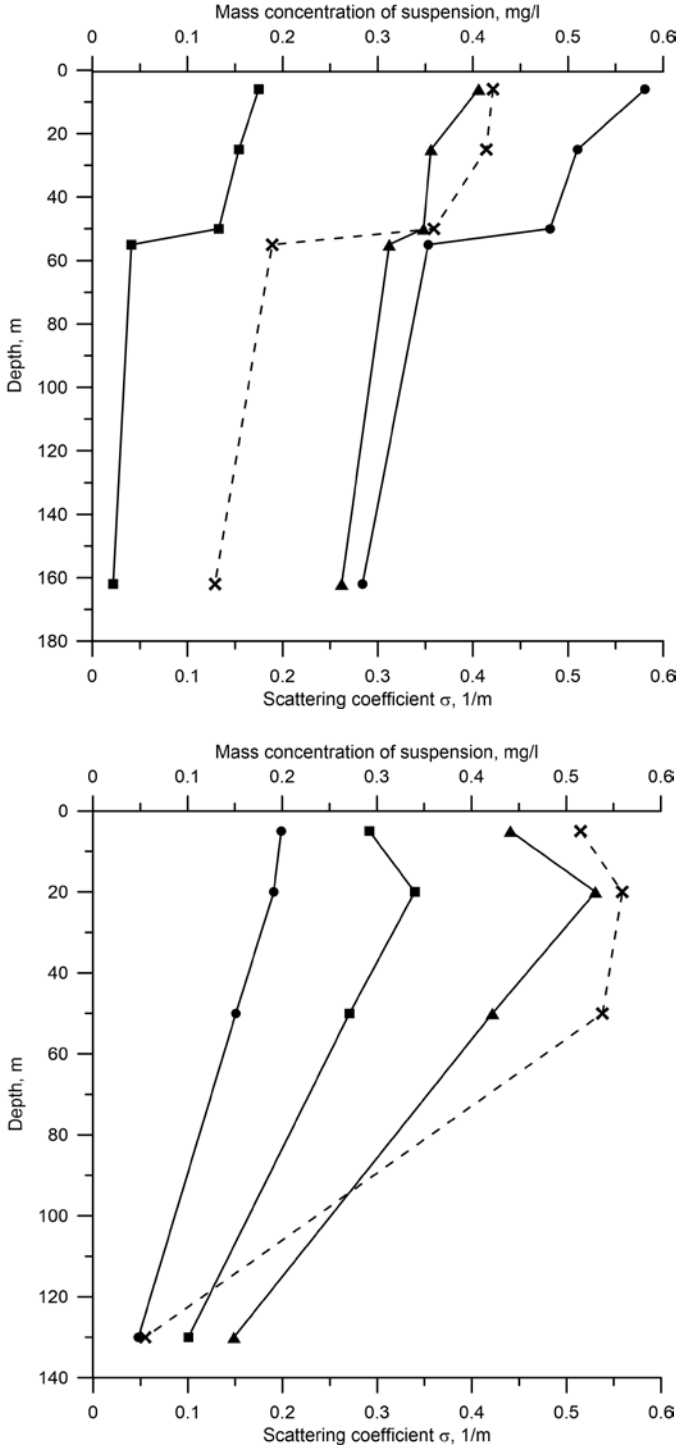
The data obtained during the 10th cruise of R/V *Akademik Vernadsky* on the suspended matter concentration in the South Ocean in the region of 20°E in January – February 1975 were compared with the data on the suspended matter distribution in the World Ocean surface waters presented in [11, p. 56] in the form of a map as per 1983.

On the map, in the area of 20° E there is data for the section from 37° to 42°S, where the range of observed concentrations of suspended matter C_{susp} is designated as 0.5–1.0 mg/l. According to our data, in January – February 1975, in the region of 37°–42°S C_{susp} = 0.396 ... 0.722 mg/l.

A comparison with the literature data on the chlorophyll concentration in the South Ocean obtained in [9] in February 2000 was carried out. This work contains measurement data in the region of 20°E, 53.5°–54.0°S, where the concentration of chlorophyll C_{chl} on the water surface is indicated within the range of 0.6–2.0 mg/m^3. According to our data, at 53°S at a depth of 5 m C_{chl} = 0.71 mg/m^3.

The comparison reveals that in both cases, the values C_{susp} and C_{chl} are of the same order, inherent in a given latitudinal zone of the South Ocean in the region of 20°E.

For comparison with the values of suspended matter concentration in other areas of the World Ocean, we present the data obtained during the same 10th cruise of R/V *Akademik Vernadsky* in the Indian Ocean (February 1975) at a section along the meridian 54°30′E from 2°00′S up to 2°00′N. The stations at the section were performed with an interval of 0.5°. Table 5 presents the comparison data, which shows the same order of suspended matter concentrations in the waters of the South and Indian oceans.



F i g. 6. Depth distribution of the scattering coefficient (dashed line) and mass concentration of organic (triangles), mineral (squares) and total (circles) suspended matter in the areas with no signs of water vertical movement at 39º S (*up*) and 55º S (*down*)

Table 5

Suspended matter concentration, mg/l, in the surface waters of the South and Indian Oceans

Suspended matter	South Ocean	Indian Ocean
Total	0.416–1.062	0.364–0.938
Organic	0.292–0.830	0.316–0.725
Mineral	0.068–0.279	0.038–0.213

Conclusion

From measurements of light volume scattering functions in the South Ocean in the region of 20°E, 37°–55°S (January – February 1975) the following was performed:

1) the data on mass concentration of total suspended matter, as well as its organic and mineral fractions were obtained;

2) the features of the vertical distribution of the organic suspension concentration in the areas of water rise and lowering and with no signs of vertical water movement were considered;

3) the relationship between the total mass concentration of suspended matter and the scattering coefficient in surface waters was established;

4) the obtained data on the concentration of suspended matter and chlorophyll and the literature data on these characteristics in the given region of the World Ocean were compared.

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Contribution of the co-authors:

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Ekaterina V. Mankovskaya – information collection, presentation of data in the text and their analysis, preparation of graphic and text materials, formulation of conclusions, paper correction

The authors have read and approved the final manuscript.
The authors declare that they have no conflict of interest.