


Original article

Errors in Calculating Density Using the CTD probe data in Suboxic Layer of the Black Sea

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Abstract

Purpose. The purpose of this work is to study the density of water in two ways in the suboxic layer of the Black Sea, to assess errors in calculating density using a standard method based on hydrophysical equipment data, to compare the results obtained with other characteristics of sea waters and to analyze the causes of these errors.

Methods and Results. The waters of the Black Sea suboxic layer were studied in May 2021 and October 2022. Water density was measured with a high-precision laboratory density meter and calculated from the CTD probe data using electrical conductivity by the EOS-80 equation of state. The turbidity values were measured by a turbidimeter while sampling. The concentrations of major ions of the major ion-salt composition in the studied samples were determined by a potentiometric titration, and their difference from the standard sea water IAPSO was assessed in the laboratory. The assessing procedure showed that, as compared to the standard sea water, the contents of SO_4^{2-} and HCO_3^- were higher on average by 0.2 and 0.6%, respectively, both K^+ and Ca^{2+} – by 0.2%, and the contents of Cl^- and Na^+ were lower on average by 0.4 and 0.3%, respectively. The content of Mg^{2+} was close to its content in standard sea water. It was found that within the range of conditional density (σ_t) 15.9–16.2 kg/m^3 , the vertical distribution of major ions was not linear, especially in relation to chlorides and sulfates.

Conclusions. As a result of determining the density of the waters of the suboxic layer of the Black Sea in two ways and comparing the obtained values, it was found that the errors in calculating the density according to the CTD probe data amount to 0.05–0.2 kg/m^3 and are due to variations in the ion-salt composition and the presence of a large suspension concentrations. The density gradient measured by a density meter is approximately twice as large as that measured by a CTD probe.

Keywords: Black Sea, suboxic layer, water density, water salinity, density measurement, CTD sounding, hydrochemical characteristics of water, ionic composition

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Introduction

Since the late 20th century, salinity measurements have been carried out mainly using CTD (conductivity, temperature, depth) probes and have been based on the ratio of seawater electrical conductivity to the conductivity of a special seawater reference sample (IAPSO Standard Seawater) (hereinafter SSW) [1]. The relationship between density, temperature, salinity and pressure is determined by the EOS-80 equation of state and salinity is calculated from electrical conductivity. Accurate salinity calculation from electrical conductivity is possible if



the relative major ion-salt composition (MIC) of seawater is constant and violation of this constancy leads to errors. The MIC undergoes some changes, leading to a variation of the electrical conductivity – salinity – density relationship, which is currently most accurately determined only for SSW obtained from a certain region of the North Atlantic. Research reveals that SSW may have chemical anomalies [2] and its electrical conductivity may vary slightly from batch to batch [3]. Variation in the electrical conductivity – salinity – density relationship is a source of error when determining seawater thermodynamic properties using the *EOS-80* equation of state, since electrical conductivity directly depends on the seawater ionic components and, to a greater extent, on the major ions [2–4]. The greatest differences between the relative MIC and the SSW composition are observed in deep ocean waters due to dissolution of carbonates, silicates and oxidation of plant residues, etc. [5, 6], in waters with high dissolved organic carbon concentrations and total alkalinity. The most pronounced ion variations are in such parts of the World Ocean as estuaries, basins with anoxic zones, as well as in thermal springs, evaporation basins, etc. [4, 5, 7].

Unlike most seas, the Black Sea has a clearly defined two-layer structure of the water column with oxic and anaerobic layers. Low-salinity waters are located in the upper sea layer, high-salinity waters – in the lower layer. Thermohaline properties of the upper layer are affected by river runoff and interaction with the atmosphere on various time scales; the properties of the lower layer depend on the influence of Marmara (Mediterranean) waters entering with the Lower Bosphorus Current, as well as vertical exchange processes [8, 9].

There is a layer of the main pycnocline (density gradient) waters between the upper and lower main layers, which differs in salinity and density from the above- and underlying layers. It is a boundary of vertical convective mixing and maintains vertical separation of oxic, suboxic and anoxic waters of the Black Sea [10]. Vertical distribution of oxygen and hydrogen sulfide depends on the depth and characteristics of the main pycnocline, which determines the existence of oxidized and restored forms of various elements: carbon, nitrogen, sulfur, manganese, iron and others. The vertical distribution of oxygen in the Black Sea is quite strongly related to density stratification [10, 11]. The main pycnocline, due to high density gradients, significantly limits the intensity of vertical turbulent exchange, and therefore the oxygen flux into deeper water layers, and is the cause for the existence of cold intermediate layer (CIL) determining its properties.

There is an oxycline below the CIL, where oxygen concentration decreases. The lower oxycline boundary corresponds to a sharp change in the vertical gradient of oxygen concentration and the density σ_t in this layer is 15.2–16.0 [12].

A suboxic layer is located below the oxycline. It was first described in [13] and its study has been the subject of many scientific papers. A suboxic layer, or zone, begins at $\sigma_t = 15.6\text{--}15.9 \text{ kg/m}^3$ and its occurrence is explained by the features of forming vertical and horizontal O_2 fluxes, vertical fluxes of suspended organic matter and H_2S . In this zone, a complex chain of redox transformations occurs through bacteria in the process of sulfate reduction, in the process of chemosynthesis, mainly involving manganese compounds, as well as nitrogen

removal (denitrification and anammox). [14, 15]. There is also a layer with an increased turbidity value; the main element of suspension mineral component is insoluble manganese oxide (MnO_2) [16, 17].

Numerous studies of complex hydrochemical structure of the Black Sea indicate significant differences in the MIC of its waters from the MIC of the World Ocean waters and IAPSO Standard Seawater, which leads to errors in calculations with the *EOS-80* equation [16–19]. This conclusion is also valid when using the *TEOS-10* equation (thermodynamic equation of state), if it was not appropriately amended by taking into account hydrochemical anomalies of macrocomponent composition relative to the SSW composition, as recommended, for example, in [20]. Complex biogeochemical processes leading to metamorphization of ionic composition in the suboxic layer can contribute to a significant underestimation of electrical conductivity values here and, therefore, salinity and density.

Previous studies of the Black Sea suboxic layer suggest that the density in this layer increases sharply – it has a leap. Then the presence of a frequently occurring layer of increased turbidity there can be explained by the presence of the largest density gradient, as was previously assumed [5, 20]. This prevents rapid deposition and dispersion of suspended particles in the water column. This study expands the understanding of the degree of biogeochemical processes influence on the seawater physical properties under non-oceanic conditions and the accuracy of their determination. Ionic variations in the deep-water composition affect the conductivity – density relationship and even small density variations can affect global circulation of ocean waters along constant-density surfaces.

This paper is purposed at studying the water density of the Black Sea suboxic layer using two methods to identify errors in determining density from CTD probe data using the *EOS-80* equation of state, as well as to compare the results obtained with other seawater characteristics and analyze the causes of these errors. To achieve these goals, the following tasks were set: study the MIC of each sample, compare it with the composition of SSW and evaluate the differences found; calculate salinity values from the sum of major ions, compare them with the values determined from the CTD probe data and calculate deviations. The obtained density and salinity values were compared with the turbidity profile and major chemical composition of the water from the samples under study.

Materials and methods

Water sampling and measurements were carried out at the Black Sea test site of P.P. Shirshov Institute of Oceanology of RAS in the Black Sea suboxic layer in the continental slope area with a maximum depth of 1300 m; sampling and measurements were taken from R/V *Ashamba* on 26 May 2021 and 13 October 2022. A total of 12 samples were taken – per 6 each year. Station coordinates: in 2021 – 44.51667°N, 37.90967°E, in 2022 – 44.51775°N, 37.90723°E. The samples were taken along isopycnals, which were located at appropriate depths during the sampling (Table 1).

Table 1

Isopycnals and depths recorded by CTD probe at the time of sampling

Depth, m	σ_t , kg/m ³	Depth, m	σ_t , kg/m ³
2021		2022	
142.2	15.86	140.6	15.92
148.1	15.98	148.1	15.99
151.3	16.04	152.6	16.05
155.1	16.09	157.3	16.11
159.4	16.15	161.4	16.16

The sampling was carried out with six 4-liter plastic Niskin bathometers mounted on a rosette equipped with an SBE 19plus CTD probe. The water samples from the bathometer were placed in sealed 1-liter containers and transported to the laboratory for subsequent analysis. Deionized water (electrical conductivity less than 0.2 $\mu\text{S}/\text{cm}$) was applied to prepare reagent solutions and dilute samples. The analyzed sample mass was measured by weighing on OHAUS laboratory analytical balances of the first accuracy class with an error of 0.001 g.

Density determination. During the sampling, seawater electrical conductivity was measured using a SeaBird 19plus CTD probe. The density from CTD data is calculated using the EOS-80 equation of state developed for ocean waters with a certain ion-salt composition. The effect of ion-salt composition variations on the accuracy of determining salinity in seawater was studied in [2, 20] and in water bodies with a composition significantly different from the oceanic one – in [21].

The water density of the studied samples was measured in the laboratory by Anton Paar DMA 5000M (Austria) precision density meter (DMA) at *in situ* temperature and atmospheric pressure. The similar device has been used as instrument from this manufacturer when developing the new thermodynamic equation of seawater state TEOS-10 [22, 23]. The samples were first filtered through GF/F Whatman membrane filter of 0.7 μm pore size to remove mineral and organic suspended matter and placed in glass containers of 250–300 ml volume. The instrument was calibrated according to the instructions. The error¹ of water density measuring was $\pm 10^{-5}$ g/cm³. Standard deviations during density measuring did not exceed $0.02 \cdot 10^{-3}$ g/cm³.

To assess the density meter accuracy, a study on SSW sample from Osil P162 (batch 162) was carried out. Modern studies of salinity of SSW various batches and assessment of their calibration accuracy, including sample P162, are discussed in [3]. The results of recent studies demonstrating high accuracy of DMA-series Anton Paar density meter are presented in [24]. The SSW density values obtained from the density meter were compared with the ones calculated using EOS-80 and TEOS-10. The density meter values differed from those calculated using EOS-80 and TEOS-10 by an average of 0.003 kg/m³, which is within the measurement error.

¹ Anton Paar, 2010. *Operating Manual DMA 4100 M, DMA 4500 M, DMA 5000 M*. Software Version: V1.70. Copyright. Anton Paar GmbH. Graz, Austria, 135 p.

This result corresponds to the conclusion from [24, p. 4] that “the results for IAPSO P160 water agree with TEOS-10 within the present measurement uncertainty”.

Density data in the work were compared in conditional density units σ_t (kg/m³) for consistency with literature sources. It is worth noting that at the depths under study, σ_t deviations from potential density σ_θ do not exceed thousandths, and *in situ* temperature differs from potential temperature by hundredths of a degree. These values are within the error range of the measuring instruments used.

Turbidity determination. During sampling, turbidity values in NTU (nephelometric turbidity unit) were measured using a Seapoint turbidimeter.

Determination of ion-salt composition. Concentrations of the major salt composition components of the samples under study (Cl^- , SO_4^{2-} , HCO_3^- , Na^+ , K^+ , Ca^{2+} , Mg^{2+}) were determined in accordance with the methods selected for the hyperhaline water analysis [21], but with regard to the Black Sea water mineralization. Reagent solutions were prepared at lower concentrations compared to that of reagent solutions for the analysis of hyperhaline waters. For example, to determine total dissolved inorganic carbon (T_{CO_2}) [25], which was calculated in grams per kilogram as HCO_3^- , we took a 0.05 M HCl solution, sulfates were titrated with 0.01 M and 0.05 M BaCl_2 solutions and chlorides – with 0.05 M solution of silver nitrate. To determine calcium and magnesium content, we used an EDTA solution (disodium salt of ethylenediaminetetraacetic acid, Trilon-B) of 0.05 M concentration. The amount of sample for analysis was adjusted as necessary. The concentrations of Cl^- , SO_4^{2-} , HCO_3^- , Ca^{2+} and Mg^{2+} were determined by potentiometric titration, K^+ – gravimetrically. Na^+ concentration was determined as the difference between the sum of anions and cations in mole equivalents. This method provides good results in case all other ions are determined with sufficiently high accuracy² [6, 26, 27]. Similar composition studies were carried out on a sample (SSW) with a practical salinity of 34.993, which was analyzed in the laboratory of P.P. Shirshov Institute of Oceanology of RAS (IO RAS) and had good agreement with the composition published in [27]. The deviations of the ion sum in the SSW from the work [27] from the ion sum obtained in the IO RAS laboratory amounted to 0.3%. This is equivalent to 0.06 g/kg for water samples from the Black Sea with a salinity of 21.

Study of the major ion concentration made it possible to determine the total mineralization of water samples, as well as to calculate an important hydrochemical characteristic of the basin – sulfate-chlorine ratio ($\text{SO}_4^{2-}/\text{Cl}^-$).

The work presents the values of major ion relative contribution to the total mineralization of each studied water sample from the Black Sea suboxic layer. The obtained values are compared with those for SSW.

Table 2 presents standard deviations when measuring the concentration of major ions in the Black Sea water, expressed as a percentage of the average mass values.

² Federal Service of Russia for Hydrometeorology and Environmental Monitoring, 1993. *Guide to the Chemical Analysis of Sea Waters: RD 52.10.243-92*. Saint Petersburg: Gidrometeoizdat, p. 130. [online] Available at: http://oceanography.ru/images/stories/lmz/docs/rd_52_10_243-92.pdf [Accessed: 14 January 2019] (in Russian).

Table 2

Value of sd (%) when determining mass concentrations of major ions

σ_t , kg/m ³	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻	Ca ²⁺	Mg ²⁺	K+
<i>May 2021</i>						
15.86	0.2	0.8	0.8	2.1	0.5	2.1
15.98	0.2	0.3	2.3	1.8	0.4	2.2
16.04	0.1	2.1	0.9	2.0	0.3	2.3
16.09	0.1	0.6	0.4	0.7	0.2	2.1
16.15	0.4	0.7	0.2	0.4	0.4	3.3
16.20	0.2	0.8	0.2	1.4	0.7	2.3
<i>October 2022</i>						
15.92	0.5	2.9	0.5	0.5	0.3	1.8
15.99	0.3	1.9	0.2	0.9	0.3	2.1
16.05	0.2	1.2	0.5	1.4	0.2	2.0
16.11	0.1	1.3	0.4	0.5	0.3	1.9
16.16	0.6	0.6	0.0	0.7	0.2	2.1
16.21	0.1	2.5	0.8	0.4	0.3	2.2

Standard deviations during sodium calculation did not exceed 0.5%. In general, the error in determining the concentrations of the major ions was hundredths of a gram.

Salinity determination. Salinity was calculated in two ways: practical salinity (SP) was calculated from the CTD probe data and practical salinity scale, as well as from the sum of major ions (SS) of the MIC. The accuracy of salinity calculation depends on the error of equipment and methods; according to [6], when calculated using electrical conductivity $\pm 0.1 \cdot 10^{-2}$ $\mu\text{S/cm}$, the sum of the major ions is $0.1 \cdot 10^{-1}$ g/kg.

Results

The results of studying water samples from the Black Sea suboxic layer, obtained in May 2021 and October 2022, are presented in Fig. 1.

Practical salinity (SP) value in 2021 according to the CTD probe data was lower than the sum of MIC components (SS) by an average of 2%, and in 2022 – by an average of 1.5%. This difference is due to the relation from [28] for ocean water:

$$SA = \frac{35.16504 \cdot SP}{35}, \quad (1)$$

where SA is absolute salinity; SP is practical salinity; 35.16504 is reference salinity value (SR). SA and SR are higher than SP by about 0.47%, since SP does not take into account carbonate content, but only the products of their decomposition – metal

oxides [28]. This is the first cause for errors in the salinity calculation from CTD probe data.

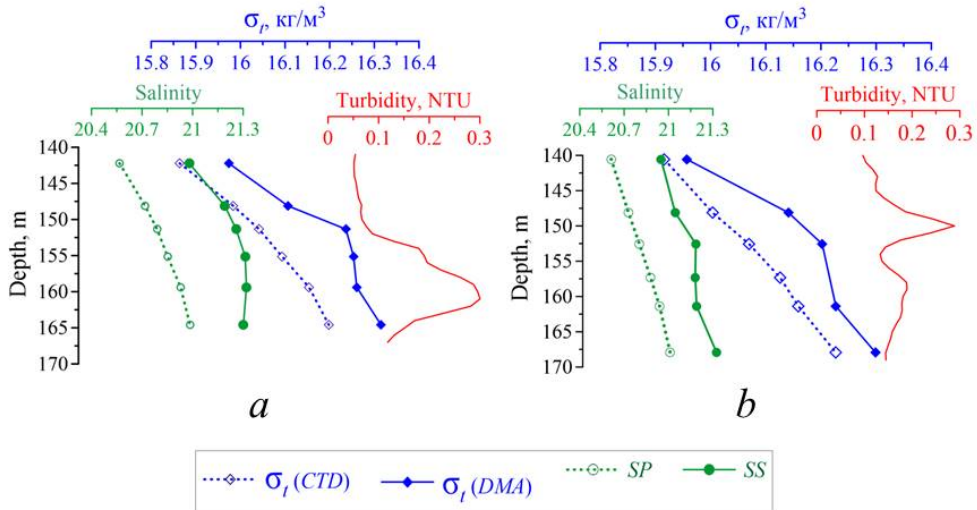


Fig. 1. Hydrophysical characteristics of water samples from the Black Sea suboxic layer: *a* – in May 2021, *b* – in October 2022. Green lines denote the results of calculating salinity and blue ones – density σ_ρ . Red line is the turbidity profile. Solid lines denote density measured by a density meter and salinity determined by a sum of major ions (SS); dotted lines indicate density and salinity calculated using the CTD probe data

Figure 1 shows that the density values calculated from the CTD probe data were lower than those measured via the density meter by 0.11–0.19 kg/m³ in 2021 and by 0.05–0.15 kg/m³ in 2022. This indicates that the density in the main pycnocline lower part actually has higher values than those calculated from electrical conductivity. In 2021, the density gradient in the suboxic zone according to the CTD probe was 0.02 kg/m³ per 1 m, and according to the density meter – 0.04 kg/m³ per 1 m, as well as in 2022 – 0.01 kg/m³ per 1 m and 0.02 kg/m³ per 1 m, respectively. On average, the actual density gradient in this layer was twice as large as that acquired from the CTD probe readings.

Fig. 1 demonstrates that a more pronounced density gradient in the suboxic zone and the upper part of the hydrogen sulfide zone is accompanied by a peak in the turbidity profile located in the region of these gradients. The turbidity peak indicates the presence of a layer of high suspended matter concentration in a given area. Suspended matter (organic and mineral) accumulation in the pycnocline region may also indicate the presence of a significant density gradient. The presence of large amounts of suspended organic matter in the Black Sea waters was noted in earlier works³ [29]. According to literature sources, this layer of increased suspended matter concentration is regularly observed in the suboxic zone. Its formation is preceded by multiple processes of water metamorphization and the main

³ Skopintsev, B.A., 1975. [Formation of the Modern Chemical Composition of the Black Sea Waters]. Leningrad: Gidrometeoizdat, 335 p. (in Russian).

element of the suspension mineral component is insoluble manganese oxide (MnO_2), which is formed due to Mn(II) oxidation [17, 30].

When suspended particles, which, as a rule, do not have electrical conductivity, enter the CTD probe measuring cell, electrical conductivity values are underestimated due to the displacement of some of the seawater ions, which are electrical charge carriers. An error in determining electrical conductivity leads to errors in calculating density and salinity. This is the second cause for different values when determining hydrophysical parameters in two ways. To determine the degree of suspended matter and variations in ion-salt composition effect on the accuracy of density measurements with a CTD probe, it is advisable to study the Black Sea suboxic layer waters using *AutoSal* precision laboratory salinity meter.

The deviation of density value measured by the density meter from the one calculated using electrical conductivity is the density determination error ($\Delta\sigma_t$), and the deviation of practical salinity value from the sum of the major ions is the salinity determination error (ΔS). The relationship of $\Delta\sigma_t$ and ΔS with density (depth) in the water column within the range of σ_t values of 15.9–16.2 is shown in Fig. 2. In 2021, $\Delta\sigma_t$ value ranged from 0.05 to 0.19 kg/m^3 and ΔS ranged from 0.32 to 0.47.

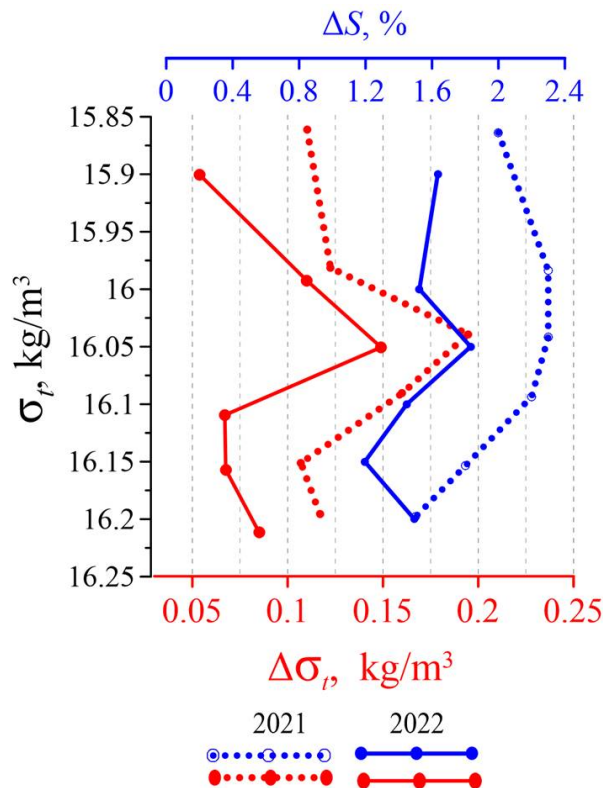


Fig. 2. Relationship between $\Delta\sigma_t$ and ΔS , and density based on the results of laboratory studies and calculations using the CTD probe data in 2021 and 2022

Fig. 2 particularly contrasts the layer with maximum $\Delta\sigma_t$ and ΔS deviations in 2021 at $\sigma_t = 16.04 \text{ kg/m}^3$ (at 151.3 m depth) and in 2022 at $\sigma_t = 16.05 \text{ kg/m}^3$ (at 152.6 m depth), i.e., under almost identical conditions. This layer corresponds to the turbidity peak shown in Fig. 1. This Black Sea layer represents the upper boundary of hydrogen sulfide zone and the lower boundary of suboxic zone [12, 14]. Figure 2 is a detailed version of Fig. 1 and allows us to see that the pycnocline has pronounced density and salinity gradients and its core is located at $\sigma_t \sim 16.05 \text{ kg/m}^3$. However, its depth can vary since the main Black Sea pycnocline is characterized by short-period fluctuations [9].

The third cause for errors in calculating salinity using EOS-80 and, to a lesser extent, TEOS-10 is due to hydrochemical anomalies in the Black Sea waters relative to the SSW. Fig. 3 presents these anomalies as relative content deviations of major ions (ΔC) in the Black Sea water samples under study from their content in the SSW and the relationship between ΔC and density. The content of ions in the SSW composition on the graph corresponds to zero. Negative values on x-axis mean that ion content is less than in SSW, and positive values – that more. The figure reveals that ΔC distribution over depth is uneven. The relative content of Cl^- and SO_4^{2-} experiences noticeable fluctuations at the suboxic layer lower boundary where the hydrogen sulfide zone begins and sulfate reduction and other biogeochemical processes causing metamorphization of waters intensify. From Fig. 3 it can be seen that the highest ΔC value corresponds to the content of chlorides and bicarbonates, sodium and calcium ions and indicates the degree of difference between the Black Sea waters and the oceanic ones. In general, the content of chlorides in the studied samples was lower by, on average, 0.4% than in SSW, and sulfate content was close to the ones in SSW (deviations amounted to an average of 0.14% – within the determination error). HCO_3^- relative content in the studied samples was consistently higher than in SSW, by $\sim 0.6\%$, and Na^+ content was lower than in SSW, by $\sim 0.4\%$ in 2021 and by $\sim 0.2\%$ in 2022.

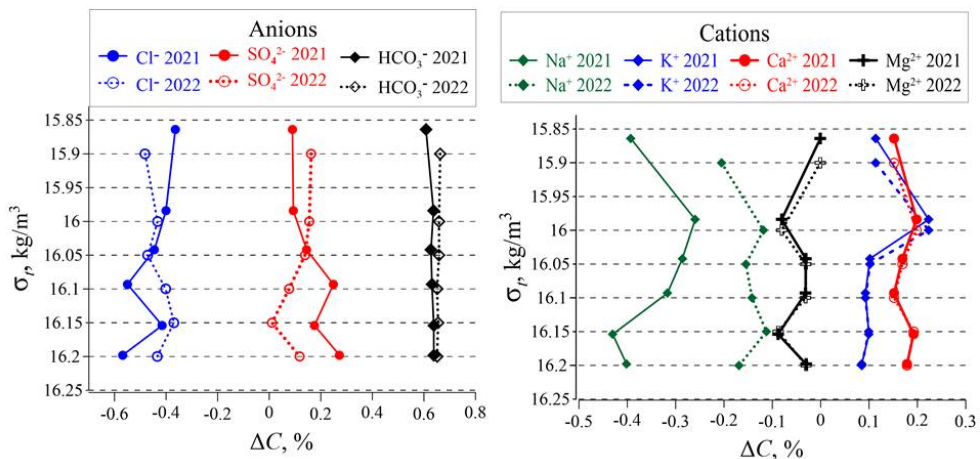


Fig. 3. Deviation (ΔC) of the relative content of major ions in the Black Sea water from their content in SSW, and their distribution by density (depth) in the suboxic layer of the Black Sea

Relative content of Mg^{2+} ions in the Black Sea water was very close to their content in the SSW; K^+ and Ca^{2+} were higher than in the SSW by $\sim 0.2\%$. The profiles of relative content of ions, and especially cations, demonstrate good correlation between 2021 and 2022.

Sulfate-chlorine ratio, being an important characteristic of a basin, reflects the constancy or variability of its ionic composition. The SO_4^{2-}/Cl^- distribution in the Black Sea suboxic layer using the studied samples as an example is shown in Fig. 4.

Figure 4 indicates that SO_4^{2-}/Cl^- distribution is not uniform in the studied σ_t range. The sulfate-chlorine ratio, which monotonically decreases to 1200 m depth [15], changes its values abruptly by 1–2% in the suboxic layer. The correlation of these changes in both 2021 and 2022 indicates a pattern of this phenomenon. In [15], a linearity violation of SO_4^{2-} concentration distribution with reference to chlorinity in the upper part of the anaerobic zone – in the area of hydrogen sulfide occurrence and to ~ 200 m depth, is also noted. The area of sulfate deficiency in relation to chlorinity coincides with the layer of increasing bacterioplankton mass, where the processes of CO_2 fixation and sulfate reduction are accelerated. The loss of sulfates in this layer, where a local maximum of suspended organic matter is frequently present, is a consequence of their reduction during sulfate reduction process.

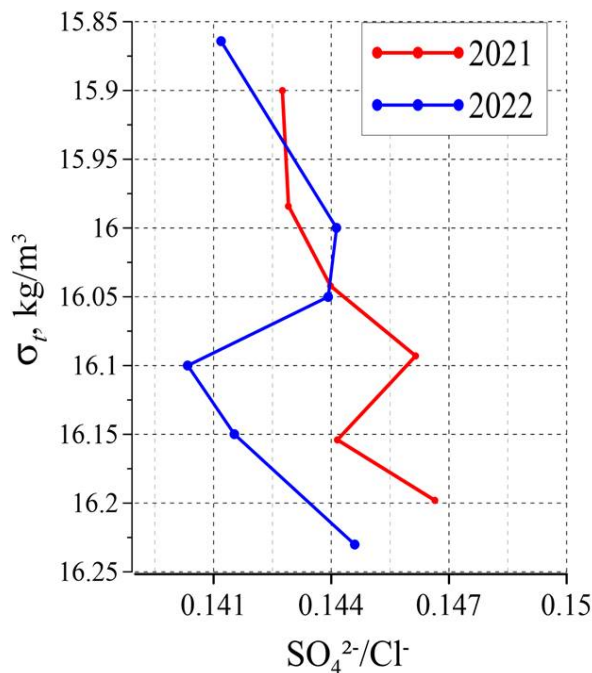


Fig. 4. Distribution of SO_4^{2-}/Cl^- by density (depth) in 2021 and 2022

Variations in the seawater ionic composition are factors that cause errors in calculations of density and salinity from electrical conductivity in the sea and in their laboratory determinations. MIC hydrochemical anomalies mainly affect electrical conductivity and the accuracy of its determination, and, accordingly, all subsequent

calculations related to it. Early studies show that electrical conductivity of solutions, including sea water, depends on the nature of the ions (unequal electrical conductivity of different ions), their concentration and variations, as well as viscosity and temperature of the water ^{4, 5} [28–31]. Increased concentrations of some ions, especially sulfates, calcium and magnesium (which enter the sea during the decay of organic residues, as a result of ion exchange reactions occurring at geochemical barriers when terrigenous suspended matter enters with continental runoff, as well as other processes [7, 20]) contribute to underestimation of salinity and density values calculated from electrical conductivity [3, 22, 27]. Hydrochemical anomalies of the Black Sea water ionic composition are the cause of deviations in the density and salinity values obtained from the CTD probe data on electrical conductivity from the values obtained in the laboratory. These deviations are especially noticeable in the surface [21, 31] and suboxic layers of the Black Sea.

Conclusions

Based on field measurements carried out with CTD probe and turbidity meter in the Black Sea, laboratory determinations of density, salinity and MIC, as well as comparison of the results obtained, it was found that CTD sounding underestimates density and salinity values in the suboxic layer. Density underestimation was 0.11–0.19 kg/m³ in 2021, 0.05–0.15 kg/m³ in 2022, and salinity underestimation was up to 2%. Density gradient obtained from the density meter data was approximately twice as large as that calculated from the CTD probe data using the EOS-80 equation.

The first cause for errors while determining density by EOS-80 using *SP* is due to practical salinity calculation, which takes into account not the carbonate content, but only the products of their decomposition – metal oxides. This results in *SP* being approximately 0.47% lower than absolute salinity.

The study and comparison of the MIC of the Black Sea suboxic layer and the SSW resulted in determination of the Black Sea water hydrochemical anomalies. Their assessment revealed that SO₄²⁻ and HCO₃⁻ contents in the Black Sea samples are on average 0.2 and 0.6% higher, respectively, K⁺ and Ca²⁺ are 0.2% higher, Cl⁻ and Na⁺ contents are on average 0.4 and 0.3% lower, respectively, than in SSW, and Mg²⁺ content is close to the one in SSW.

It was found that nonlinear distribution of major ions (ionic variations) in the chemical composition of suboxic layer waters is most strongly expressed in an abrupt SO₄²⁻/Cl⁻ variation by 1–2%. Ionic variations, and especially SO₄²⁻/Cl⁻ change, are the second cause of errors in determining salinity and density from electrical conductivity, i.e., from CTD probe data.

As a result of determining density values of the samples under study obtained in two ways and comparing them with the turbidity profile, it was found that

⁴ Mushkamarov, N.N., 2008. *Physical and Colloidal Chemistry. Textbook for Universities (With Problems and Solutions)*. 3rd Ed., Expanded. Moscow: Medical Information Agency LLC, 295 p. (in Russian).

⁵ Svarovskaya, N.A., Kolesnikov, I.M. and Vinokurov, V.A., 2017. *Electrochemistry of Electrolyte Solutions. Part I. Electrical Conductivity: Study Guide*. Moscow: Publishing Centre of I.M. Gubkin Russian State University of Oil and Gas (NRU), 66 p. (in Russian).

the layer of increased suspended matter concentration (turbidity peak) was in the range of maximum $\Delta\sigma_t$ values in ~ 160 m layer at σ_t equal to 16.04–16.05 kg/m³). It follows from this that the increased concentration of suspended matter underestimates the electrical conductivity values, and, consequently, the values of salinity and density calculated using it; this is the third cause of errors in determining density and salinity from CTD probe data.

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The authors have read and approved the final manuscript.

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