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Original article

Changes in the Black Sea Thermohaline Structure below the Main Pycnocline Based on Ship Observations

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Abstract
Purpose. The work is purposed at studying the changes in distribution of water thermohaline characteristics in the main pycnocline and below (100–400 m) in the northern and northeastern parts of the Black Sea.
Methods and Results. The data of hydrological measurements (conductivity, temperature and depth) obtained by the scientists of Marine Hydrophysical Institute, RAS in the 20 cruises of R/V “Professor Vodyanitsky” in the northern and northeastern parts of the Black Sea in 2016–2021 were used. A gradual increase in water temperature and salinity below the main pycnocline was revealed; it extended up to the 16.9 kg/m^3 (~ 370 m) isopycne. For the indicated period, the worming constituted 0.14 °C for isopycne 16.3 kg/m^3 (~ 150 m), 0.09 °C for isopycne 16.5 kg/m^3 (~ 180 m), and 0.02 °C for isopycne 16.9 kg/m^3 (~ 370 m). During the same period, the salinity increase within the range of isopycnes 15.9–16.1 kg/m^3 amounted to 0.03 PSU. The changes in temperature and salinity have resulted in the rise of isopycnic surfaces. The 15.8 kg/m^3 isopycne rose from the 106 m horizon in 2016 to the 96 m one in 2021, and the 16.1 kg/m^3 isopycne – from the 126 m horizon to the 115 m one. The rates of isopycne rises within the range 15.8–16.3 kg/m^3 were maximum and amounted to 3–3.5 m/year.
Conclusions. In the last decade, the trends in increasing temperature and salinity in the upper 200–300 m layer are typical of the whole Black Sea area. Besides, this phenomenon is observed much deeper, up to the ~ 400 m depth. The intensity of warming decreases with depth. A comparison with the data from earlier measurements has shown that just during the indicated period, significant changes, particularly evident since 2018, took place. In general, the changes observed in the Black Sea thermohaline structure below the main pycnocline can be induced by the climatic changes, as well as by the increased inflow of the Mediterranean Sea waters (also transformed due to general climate warming) through the Bosphorus Strait.

Keywords: temperature, salinity, Black Sea, pycnocline, thermohaline structure, climatic changes

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Introduction

Climate warming and changes in atmospheric circulation in recent years are increasingly affecting the process of formation of the thermohaline structure of the Black Sea waters. Many studies have noted warming and salinization of surface waters and the active layer of the sea over periods of at least 10 years. It has been shown that over the period 1980–2020, the increase in sea surface temperature in the Black Sea significantly intensified and amounted to 0.5 °C/10 years [1, 2]. The trend toward increasing salinity in the surface layer over the period 2000–2020 was 0.18/10 years, indicating a high rate of seawater salinization over the last 20 years [2].

Significant changes are observed in the cold intermediate layer (CIL) of the sea (50–100 m). The CIL temperature is rising, and the layer itself is gradually becoming thinner and “eroded” [3–8]. The last significant renewal of the CIL within its classical boundaries (the 8 °C isotherm), according to shipboard measurements, was recorded in 2017 [9–11].

In the underlying layers (150–300 m), a pronounced warming trend has also been reported based on numerical modeling results [12] and shipboard monitoring data from a part of the Black Sea (the Gelendzhik area) [13]. In [13], increasing trends in temperature and salinity were found in the upper 200–300 m layer in 2010–2020, and it was suggested that this could be caused by an increased inflow of Lower Bosphorus Current waters into the layer with a potential density of 14.6–16.2 kg/m^3.

According to [14], which presents an analysis of Argo float data for the period 2005–2021, the temperature of the Black Sea waters increased noticeably after 2010. Moreover, the temperature increase was observed down to depths of 700 m, which differs significantly from previous observations of warming down to 300 m. The study also shows that such warming of waters at depths of 150–700 m is associated with the inflow of warm and saline waters of Mediterranean origin through the Bosphorus Strait [15, 13, 16], as well as with an increase in the temperature of these so-called “Bosphorus intrusions” spreading throughout the sea.

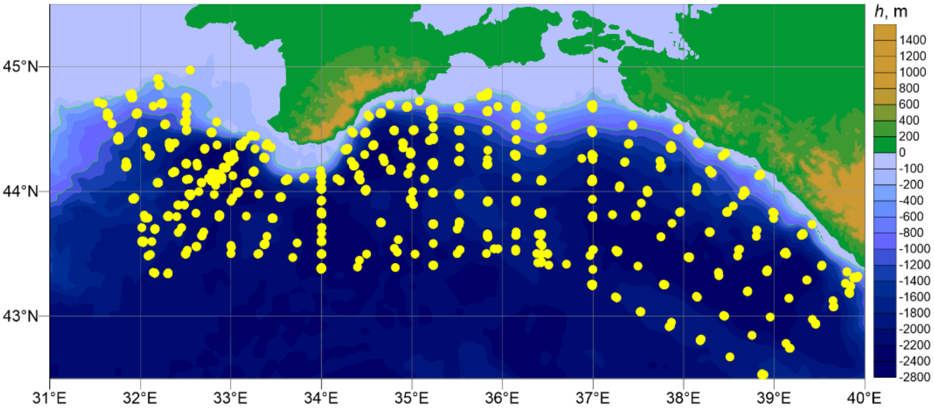
A disadvantage of data obtained from Argo floats or from oceanographic sections is their uneven distribution in space and time and, in the case of floats, the lack of sensor calibration over long time intervals. Contact measurements collected on a regular grid over a short period are preferable. The accuracy of such measurements is higher because the instruments undergo annual metrological verification.

Starting from 2016, Marine Hydrophysical Institute (MHI) has annually carried out expeditionary research in the northern and northeastern regions of the Black Sea. CTD (conductivity, temperature, depth) sounding is traditionally performed at hydrological stations during cruises.

This work aims to investigate changes in the distribution of thermohaline characteristics of the Black Sea waters in the main pycnocline layer and below (100–400 m) based on the analysis of CTD measurement data from 20 cruises of the R/V *Professor Vodyanitsky* from 2016 to 2021.

Materials and methods

The work uses hydrological measurement data from 20 expeditions of Marine Hydrophysical Institute of RAS carried out in the northern and northeastern parts of Black Sea in 2016–2021. The location of stations in the deep-water part of the sea (> 200 m), without division by cruises (as many stations were repeated), is shown in Fig. 1.



F i g. 1. Hydrological stations during the expeditions in 2016–2021

The number of data sets and the measurement dates are given in the Table. In the first 12 expeditions (cruises 87–108), CTD measurements were performed using an SBE911+ probe; starting from cruise 110, an IDRONAUT OCEAN SEVEN 320 PlusM sounding complex was used. The measurement results were interpolated onto a 1 m grid. According to the instrument descriptions, temperature and salinity measurements had an initial accuracy of 10^{-3} °C and 10^{-3} PSU, respectively.

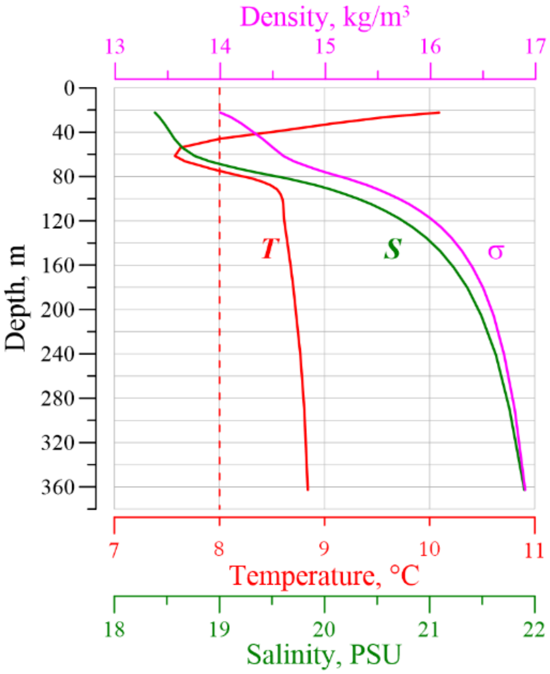
Data on cruises and hydrological measurements at deep-sea stations (> 200 m)

Cruise number	Date of measurements	Number of measurements	Year
87	July 1–18	70	2016
89	Sept. 30 – Oct. 19	60	
91	Nov. 16 – Dec. 2	46	
94	Apr. 22 – May 6	72	2017
95	June 14 – July 3	89	
98	Nov. 15–27	47	
101	Dec. 14–26	49	
102	June 9–30	97	2018
103	Aug. 24 – Sept. 18	97	
105	Nov. 18 – Dec. 9	65	
106	Apr. 20 – May 10	84	2019
108	July 12 – Aug. 3	99	
110	Oct. 4–21	78	
111	Dec. 6– 27	81	
113	June 4–27	93	2020
114	Sept. 15 – Oct. 8	63	
115	Nov. 27 – Dec. 16	38	
116	Apr. 22 – May 15	94	2021
117	June 29 – Aug. 9	100	
119	Sept. 3–26	82	

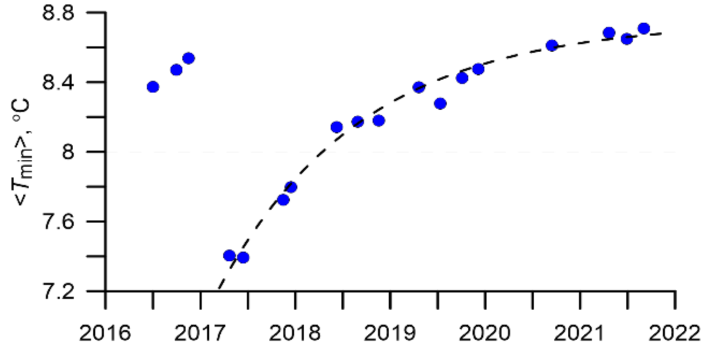
For each expedition, average profiles of hydrophysical parameters (temperature, salinity, and density) over the set of stations were calculated using isopycnic averaging. That is, averaging was performed not at constant depth levels (horizons), but at constant density values (isopycnes). This method is more informative than averaging over constant depth levels due to the dome-shaped form of isopycnal surfaces in the Black Sea caused by the cyclonic nature of the large-scale circulation [17]. In the central part of the sea, the depth of isopycnes is shallower, whereas in the slope region it is greater; the variability range can be ~ 100 m.

Results and discussion

The vertical distribution of Black Sea water temperature below the main pycnocline is characterized by a slow increase with depth. The averaged vertical thermohaline structure obtained during cruise 95 is shown in Fig. 2. The expedition was carried out in 2017, when the only significant renewal of CIL waters within their "classical" boundaries (the 8 °C isotherm) over the last 10 years was observed. After this event, the warming of waters in the CIL core was described by the following dependence: $\langle T\mathrm{min}\rangle(t) = 7 + 1.75\,(1 - \exp(-(t - 2017)/1.5))$, where t is time in years (Fig. 3).

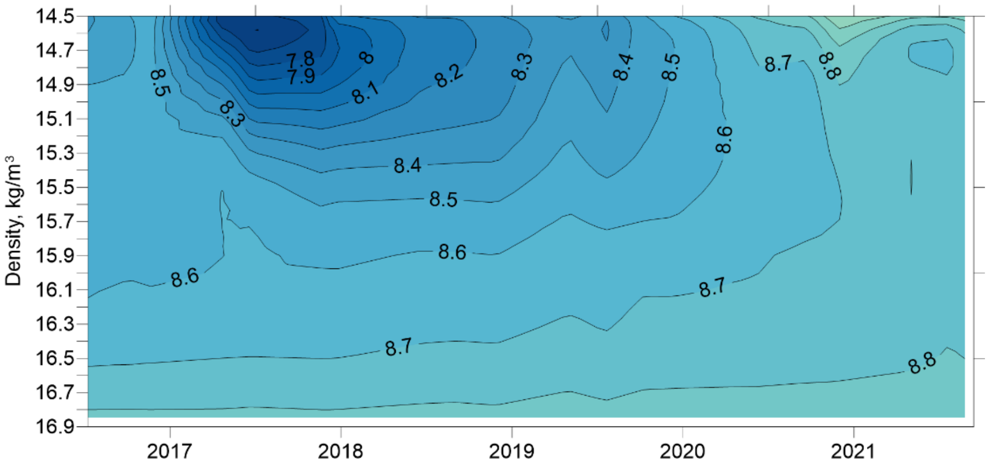


F i g. 2. Averaged isopycnic vertical profiles of water temperature (T), salinity (S), and density (σ) during the 95th cruise of the R/V *Professor Vodyanitsky*. The red dashed line indicates the location of the 8 °C isotherm



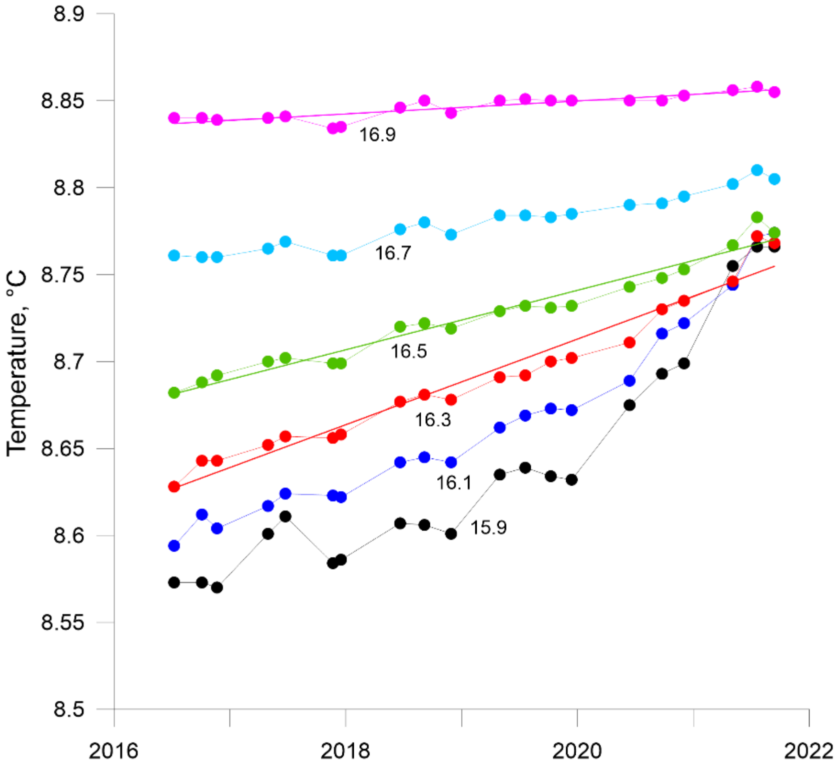
F i g. 3. Average values of the minimum water temperature in the profiles at the stations in 2016–2021. The black dashed line shows the approximating function

According to our data, over the period 2017–2021, the water temperature in the CIL core increased by ~ 1.2 °C. For comparison of warming rates, references can be made to [6], which showed that the temperature in the CIL core increased by more than 1 °C over 20–30 years (1992–2019). According to the present work, such a temperature increase occurred in just 4 years. At the same time, a rise of isotherms is noted, with the rate of rise gradually increasing from 2018 onward (Fig. 4). For example, the 8.7 °C isotherm rose from an average depth of 194 m in 2016 to 64 m in 2021, i.e., by 130 m. A sharp jump from 128 to 64 m occurred in the last two considered years (2020–2021). Similar results were obtained from shipboard monitoring data in the Gelendzhik area in 2010–2020: the 8.7 °C isotherm rose from an average depth of 242 m in 2010 to 121 m in 2020, with a sharp jump in the last year [13].



F i g. 4. Dynamics of isotherms in potential density coordinates in 2016–2021

Next, we consider the water temperature data below the main pycnocline-halocline. Average temperature values indicate significant warming of Black Sea waters in the density range of 15.9–16.9 kg/m^3 (Fig. 5), which corresponds to depths from ~ 100 to ~ 400 m (Fig. 2). The intensity of such warming decreases with depth.



F i g. 5. Changes in average water temperature for 2016–2021 at the isopycnal surfaces 15.9–16.9 kg/m^3. Straight lines indicate linear trends

In [14], based on Argo float data, the following warming estimates for the northeastern Black Sea for 2005–2021 were obtained: ~ 0.2 °C at 150 m depth; ~ 0.11 °C at 200 m; ~ 0.05 °C at 300 m; ~ 0.025 °C at 500 m.

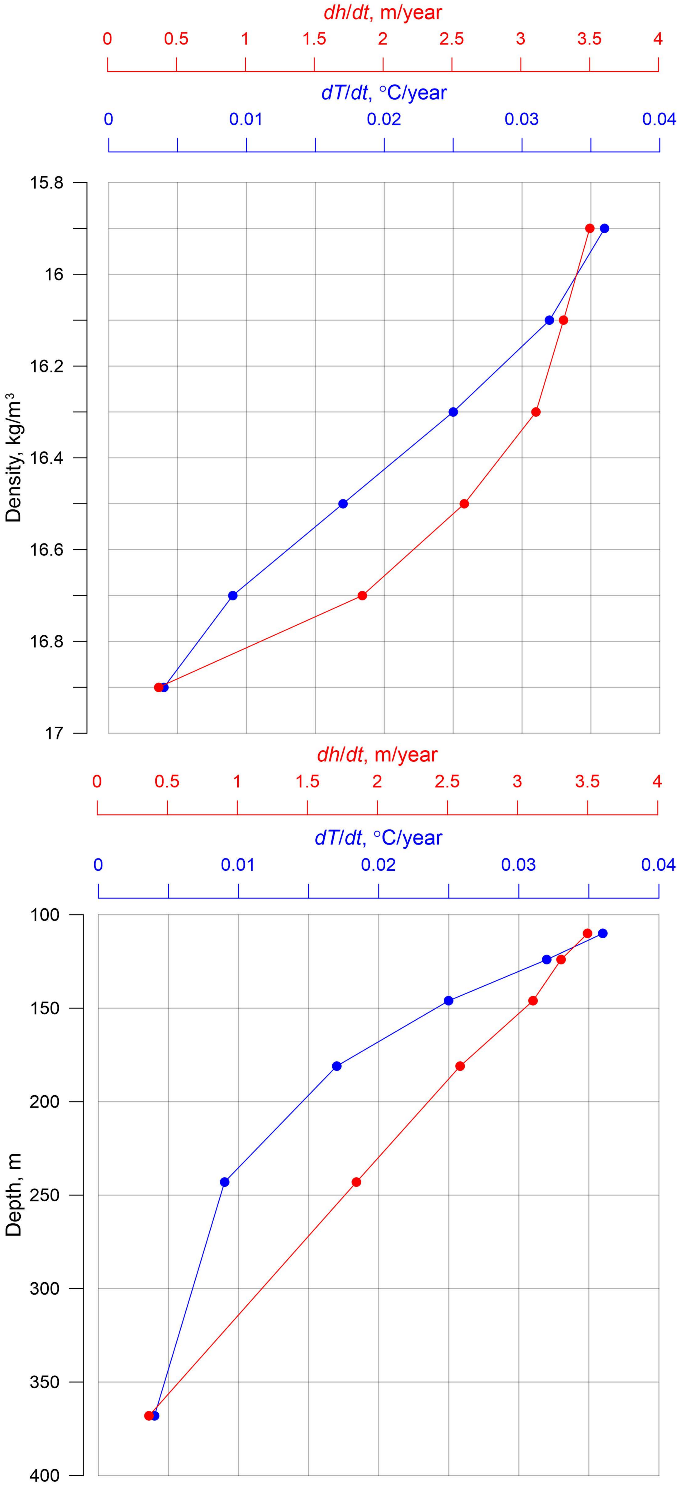
According to our data, the warming over the period 2016–2021 was as follows (Figs. 5, 6):

– 0.14 °C for the 16.3 kg/m^3 isopycne (average depth ~ 150 m); the temperature increase rate was 0.025 °C/year;

– 0.09 °C for the 16.5 kg/m^3 isopycne (average depth ~ 180 m); the temperature increase rate was 0.017 °C/year;

– 0.02 °C for the 16.9 kg/m^3 isopycne (average depth ~ 370 m); the temperature increase rate was 0.004 °C/year.

Comparison of water temperature increase estimates reveals that the main changes in the warming process at ~ 100–400 m depths occurred during the period 2016–2021. The same is noted in [14], where it is shown that warming at ~ 100–700 m depths became continuous and progressive after 2014.



F i g. 6. Temporal gradient of water temperature and depths of isopycnal surfaces as functions of density (*top*) and depth (*bottom*) for 2016–2021

To assess the increase in water temperature in the Black Sea below the main pycnocline, we also present the results of shipboard measurements for 2004. The average water temperature in that year was 8.47 °C on the 16.3 kg/m^3 isopycne, 8.61 °C on the 16.5 kg/m^3 isopycne, and 8.84 °C on the 16.9 kg/m^3 isopycne. That is, the total increase in water temperature on the corresponding isopycnal surfaces over the period 2004–2021 was:

– 0.35 °C for 16.3 kg/m^3 isopycne;

– 0.17 °C for 16.5 kg/m^3 isopycne;

– 0.02 °C for 16.9 kg/m^3 isopycne.

The latter value indicates that the warming of waters below the main pycnocline during the considered period, 2016–2021, progressed steadily and extended down to the 16.9 kg/m^3 isopycne (average depth ~ 370 m). This is due to the inflow of warm waters of Mediterranean origin, as shown in [14, 18]. For example, in June 2002, a maximum deepening of such waters was found at a depth of ~ 450 m, with a layer thickness of ~100 m and a temperature deviation from the mean temperature-salinity relationship of ~ 0.02 °C [19]. According to our shipboard observations, in June 2017, elevated temperature values were observed in the depth range of 100–400 m, with a temperature deviation reaching 0.04 °C [18].

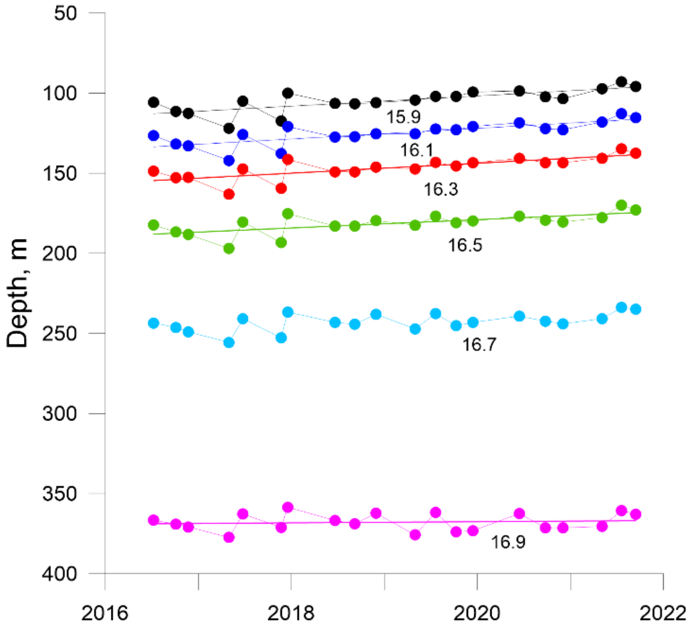
It should be noted that salinity values below the main pycnocline show a less pronounced trend; salinity increases more slowly than temperature. The increase in salinity within the range of the 15.9–16.1 kg/m^3 isopycnes was 0.03 PSU over the period 2016–2021. Similar results were obtained from measurements in the northeastern Black Sea near Gelendzhik [13].

In that study, as well as in [20], trends of isopycnal rise were noted: for example, the 15.8 kg/m^3 isopycne rose on average from 143 m in 2010 to 134 m in 2019. In 2020, an even more noticeable jump was observed, to 124 m. Data from our shipboard survey measurements confirm this trend (Fig. 7).

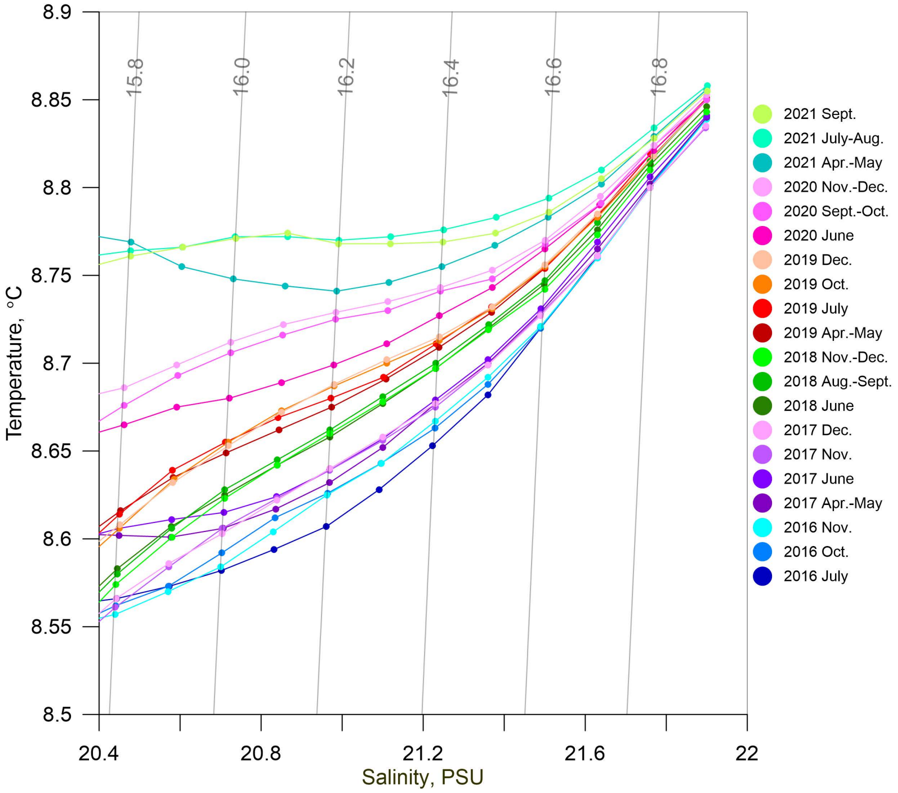
The 15.8 kg/m^3 isopycne rose from an average depth of 106 m in 2016 to 96 m in 2021. This isopycne corresponds on average to the position of the upper boundary of the suboxic zone, i.e., the layer with almost no oxygen. This may mean that the thickness of the upper productive layer of the Black Sea decreased over the considered observation period. However, according to [20, 21], the rise of isopycnes does not mean a rise in the boundaries of the suboxic and hydrogen sulfide zones; their position is not strictly isopycnic. For example, according to expeditionary data from 2017–2019, the upper boundary of the suboxic zone was located in the interval of isopycnes 15.7–15.85 kg/m^3 [22].

The 16.1 kg/m^3 isopycne rose on average from 126 m in 2016 to 115 m in 2021. In the vicinity of this isopycne, the upper boundary of the hydrogen sulfide zone is observed. According to expeditionary data from 2017–2019, this boundary was located in the interval of isopycnes 16.10–16.15 kg/m^3 [22]. The rates of isopycnal rise within the range of 15.8–16.3 kg/m^3 are maximal and amount to 3–3.5 m/year (Fig. 6). The position of these isopycnal surfaces (on average) determines the location of the suboxic water zone (redox layer) [21–23].

The nature of changes in the thermohaline structure of seawater is also reflected in the T, S-diagrams for the layer from ~ 100 to ~ 400 m for 2016–2021 (Fig. 8). The figure clearly illustrates a gradual increase in temperature and salinity extending down to the 16.9 kg/m^3 isopycne.



F i g. 7. Changes in the average depths of the 15.8–16.9 kg/m^3 isopycnal surfaces in 2016–2021. Straight lines indicate linear trends



F i g. 8. *T*, *S*-diagrams of Black Sea waters in the isopycnal range 15.8–16.9 kg/m^3 for 2016–2021

The observed changes in the thermohaline structure of Black Sea waters below the main pycnocline can be associated with climate change in general, as well as with an increased inflow of Mediterranean waters through the Bosphorus Strait, which have also been transformed due to overall climate warming.

For example, in [24], based on CTD measurements and current measurements in the Bosphorus Strait at the exit to the Black Sea for the period 1996–2010, positive trends were obtained at a depth of 67 m in the time series of water temperature and salinity, as well as in time series of volume fluxes. The increases were ~ 0.06 °C/year and 0.04 PSU/year, respectively; the trend in volume flux was 170 (m^3/s)/year (~ 5 (km^3/year)/year). Such changes lead to an increase in water density; the water sinks to deeper horizons corresponding to its density, causing, in turn, a rise of lower-density isopycnal surfaces.

Conclusion

Global and regional climatic changes affect the thermohaline structure of Black Sea waters. This work presents estimates of temperature and salinity variability in the main pycnocline and below, based on *in situ* CTD measurement data from 20 cruises of the R/V *Professor Vodyanitsky* in 2016–2021. Average values for each expedition were obtained by isopycnic averaging, which allows more accurate identification of structural changes in stratified water bodies.

The presented material shows a significant warming of Black Sea waters in the density range of 15.9–16.9 kg/m^3, which corresponds to depths of 100–400 m. The intensity of such warming decreases with depth.

The observed warming of waters below the main pycnocline during the considered period progressed steadily and reached the depths of the 16.9 kg/m^3 isopycne (average depth ~ 370 m). Comparison with data from earlier measurements reveals that significant changes occurred precisely during the indicated period, becoming especially evident after 2018.

The increase in water salinity below the main pycnocline shows a less pronounced trend; it increases more slowly than temperature. Nevertheless, below the main pycnocline, salinity makes the main contribution to water density, which leads to a rise of isopycnal surfaces. The maximum rise is observed on the 15.8–16.3 kg/m^3 isopycnes.

Thus, as previously assumed, the trends of increasing temperature and salinity in the upper 200–300 m layer in the last decade are characteristic of the entire Black Sea. Moreover, they extend much deeper, down to ~ 400 m. Analysis of Argo float data also confirms the ongoing changes in the thermohaline structure of Black Sea waters.

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Alexey N. Morozov – data processing, analysis and interpretation of research results, manuscript editing

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