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Original article

Trends in Acceleration of Climate Changes in the Thermohaline Structure of the Black Sea Upper Layer

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Abstract
Purpose. The purpose of the study is to assess the trends in a change of the Black Sea thermohaline structure on the interannual time scales in 2000–2020 based on three reanalyses performed using different methods, as well as direct observations.
Methods and Results. Four datasets are applied to perform the research. The first one is an array of temperature and salinity profiles on a regular grid with a 10-day time resolution and a 10′ × 15′ spatial resolution for 2000–2021, which is based on the data of 13952 oceanographic stations. The second set is formed according to the results of reanalysis carried out using the MHI Black Sea circulation model. The ERA-5 atmospheric reanalysis results are used as an atmospheric forcing. The satellite data on sea surface temperature and altimetry are assimilated in the model. The third dataset represents the reanalysis results obtained based on the NEMO model regional configuration. The atmospheric forcing is also preset using the ERA-5 reanalysis results. The following data are engaged in assimilation: the arrays of temperature and salinity profiles, and the satellite altimetry and sea surface temperature measurements. The BLKSEA_MULTIYEAR_PHY_007_004 product of the Copernicus Marine Service containing the reanalysis of daily average fields for the Black Sea basin from 01.01.1993 to 30.06.2021 constitutes the fourth set. The described four data sets have made it possible to analyze the trends in temperature and salinity changes in the upper layer of the Black Sea.
Conclusions. It is shown that since 2005, an increase in the average sea surface temperature in the Black Sea area has resulted in a tendency towards disappearance of the cold intermediate layer in its traditional understanding as a subsurface layer with a water temperature ≤ 8 °C. Besides, the accelerated sea water warming within the main pycnocline is observed. The sea haline regime in 2012–2015 is characterized by a transition from freshening to salinization of the sea surface layer that is related to a change in the external budget of fresh water, and a long-term increase in water salinity in the main pycnocline.

Keywords: retrospective analysis, Black Sea, seawater temperature, salinity, climatic changes, thermohaline structure

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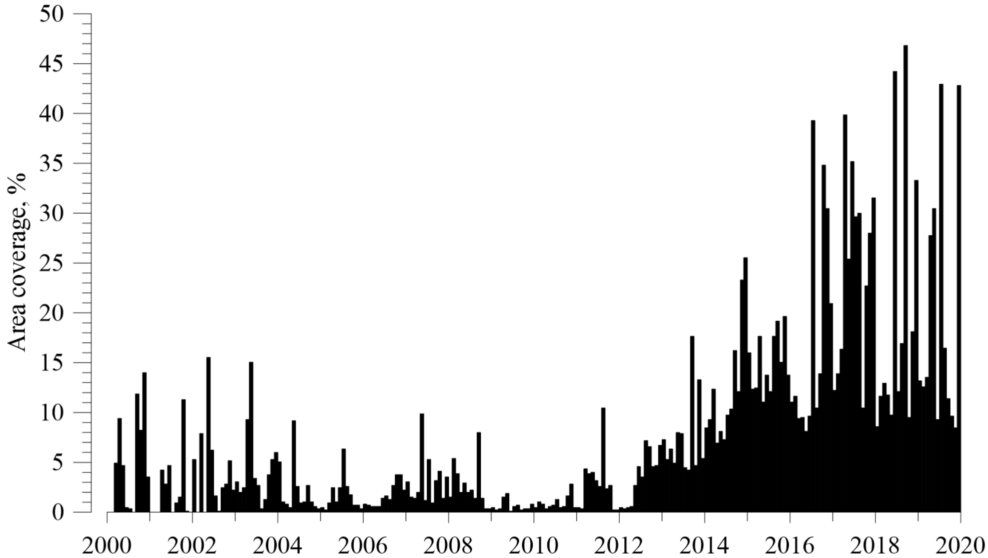
Introduction

The Black Sea is a semi-enclosed body of water, completely surrounded by land and connected to the World Ocean via the Mediterranean and Marmara Seas, as well as a network of straits. The Black Sea basin has a positive water balance and a distinctive thermohaline structure with a sharp halocline and a cold intermediate layer (CIL). In addition, the Black Sea exhibits unique interannual and long-term variability in its thermohaline structure, differing significantly from other seas. In the main pycnocline layer, the influx of Mediterranean waters results in a gradual and continuous increase in temperature and salinity. In the upper layer of the sea, this trend changes to well-defined interdecadal fluctuations [1]. Various combinations of positive and negative anomalies in the heat and salt content of the top 100 meters of the Black Sea form a sequence of 10–20-year periods in its hydrological regime – cold and salty in the 1950s, warm and salty in the 1970s and 1980s, and so on. At the turn of 2010–2015, there was a transition from the freshened, warm period of the 2000s to the current state, which is characterized by higher temperatures and salinity [1–3].



F i g. 1. Relative portion of coverage of the Black Sea deep part (%) with oceanographic observation data in 2000–2020

A more detailed study of the transition to modern climatic conditions is complicated by the sharp reduction in the Black Sea instrumental measurements between 1996 and 2013 (Fig. 1). The coverage of its deep-water region fell from 70–100% in the 1980s to 0–10%, and only increased to 20–40% from 2014 due to the resumption of oceanographic surveys in the Russian Federation economic zone and the operation of profiling floats. The existing gap in observational data can only be filled using reanalysis arrays created based on numerical thermohydrodynamic models. Work [4] presents the results of an assessment of trends in the state of the marine environment on interannual timescales between 2000 and 2020, based on three reanalyses performed using different methods, as well as direct observations during periods when the Black Sea area was covered fairly uniformly. Comparing the results of calculations performed using different methods made it possible to determine general climatic trends and identify how they differ in reconstructing natural processes during certain periods. This work demonstrates, in particular, that the previously observed trend of sea water warming, which led to the episodic disappearance of the CIL within its traditional boundaries, with a water temperature in the core below 8 °C, accelerated significantly after 2012. Consequently, CIL renewal ceased completely in winter by 2020.

This work is purposed at providing a detailed analysis of thermal changes in the upper layer of the Black Sea in 2000–2020 and discussing trends in seawater salinity.

Methods for assessing trends in changes of the Black Sea thermohaline characteristics

In this study, trend assessments of changes in the Black Sea thermohaline characteristics were conducted, as in [4], according to direct observations and the results of three reanalyses based on different methods.

Direct analysis of observational data. A temperature and salinity data array was prepared on a regular grid (array 1) with a spatial resolution of 10′ × 15′ and a discreteness of 10 days. Gandin's optimal interpolation method was applied to create this array [1]. The interpolation equation system was solved using the Gauss method and the observation error was estimated as the sum of the instrumental error and the standard deviation of the mesoscale variability. The average monthly climatic fields of temperature and salinity were used as the norm for the anomalies. Assuming isotropy of the spatial correlation functions in the Black Sea [5, 6], we applied the approximation from [5] as the autocorrelation function to approximate the structure of the Gaussian fields depending on depth. A total of 16,845 profiles were prepared for the period 2000–2021 at regular grid nodes, based on 13,952 oceanographic stations. In this case, we set a condition whereby the number of extrapolation cases used to fill the free space was kept to a minimum.

Reanalysis based on the Black Sea circulation model of Marine Hydrophysical Institute (MHI). The reanalysis was based on the MHI Black Sea circulation model, which relies on an approximation of a system of primitive ocean dynamics equations [7]. We applied a version of the model with a spatial step of 4.8 km, which provided an adequate description of both large-scale circulation and synoptic processes. The model contains 35 computational z-levels vertically, which converge towards the sea surface. Climatic discharge values were specified at the mouths of major rivers. To take into account water exchange through the Bosphorus Strait at horizons corresponding to the lower Bosphorus current, velocities were preset based on the climatic discharge rate and a salinity value of 36. At the horizons corresponding

[1] Gandin, L.S., 1963. *Objective Analysis of Meteorological Fields*. Leningrad: Gidrometeoizdat, 287 p. (in Russian).

to the upper Bosphorus current, where water flows out of the Black Sea, a constant velocity value was preset to ensure water balance for the time period under consideration.

The circulation model equations were solved using the parameters from the ERA-5 atmospheric reanalysis (ECMWF) [8] for the boundary conditions on the free sea surface: surface wind, heat and fresh water fluxes, and solar radiation. We applied the atmospheric fields with the spatial resolution of 0.25° × 0.25° and a time frequency of 1 h.

The Black Sea circulation model used satellite sea surface temperature (SST) and altimetry data. The surface temperature data were prepared by CMEMS as a daily gridded dataset with a spatial resolution of 0.05° × 0.05°. The altimetry data (also from CMEMS) were prepared as L4 gridded sea level anomalies (SLA) with a spatial resolution of 0.15° × 0.15°, calculated with respect to the 20-year mean (1993–2012). To be assimilated into the circulation model, the sea level anomalies were transformed into free surface elevation using the mean dynamic topography, which was calculated from the reanalysis results (1993–2012) [9]. The annual mean temperature and salinity profiles were prepared based on all available hydrographic surveys and Argo float data for the period under consideration.

SST assimilation was performed using the relaxation method. Satellite SST values were compared with model surface temperature values once a day. Sources on the right-hand side of the heat transport – diffusion equation proportional to the temperature value discrepancy were included at measurement points on model horizons which were part of the upper mixed layer.

We used the algorithm described in [10] to assimilate satellite altimetry data. The temperature and salinity profiles were adjusted proportionally at each point according to the difference between the measured and modelled free sea surface elevation values. In this case, depth-dependent weighting factors were calculated using cross-covariance functions of errors in level, salinity and/or temperature.

In accordance with the annual average profiles obtained from all available contact measurement data, temperature and salinity values were corrected at depths below 500 m. This dataset is further identified as array 2.

Reanalysis based on the NEMO model. The reanalysis (hereinafter referred to as array 3) was carried out using the regional configuration of the NEMO [2] ocean dynamics numerical modeling complex. This allows the dynamics and trends of hydrophysical parameters in the Euxine Cascade seas (the Black Sea, the Sea of Azov and the Marmara Sea (BAMS24)) to be reconstructed [11]. The computational grid is geographic and covers the marked basins with spatial steps of ≈ 4.6 × 4.6 km.

The atmospheric impact was specified based on ERA-5 (ECMWF) reanalysis fields [8]. The air temperature and humidity fields were considered at a height of 2 m, while the horizontal wind velocity components were considered at a height of 10 m. The downward long-wave and short-wave radiation flows, total precipitation and precipitation in the solid phase were also taken into account. The meteorological

[2] Madec, G. and the NEMO Team, 2008. *NEMO Ocean Engine*. Note du Pôle de Modélisation de Institut Pierre-Simon Laplace (IPSL). 412 p.

parameters noted with initial discreteness in time were applied to calculate the total heat, mass and wind friction stress flows according to the CORE [3] protocol's bulk formulas.

The regional configuration takes into account the climatic discharge of the 16 rivers in the Black Sea basin. For the Sea of Azov and the Kerch Strait, where water exchange occurs, real changes in the water balance over time are considered. For this purpose, data on the volumetric runoff of the Don and Kuban rivers are used [4]. At the exit from the Dardanelles Strait to the west of Marmara Island, boundary conditions are set on an open liquid boundary. Quasi-real changes in sea level, barotropic and baroclinic current velocities, temperature and salinity obtained from the CMEMS global reanalysis system products are used for this purpose [5].

To carry out a retrospective analysis for the period 2000–2021, we utilized the following observational database:

– a combined array of temperature and salinity profiles in the Black Sea from the EasyCORA arrays of the CMEMS service (1999–2021) and the SeaDataNet oceanographic database (https://www.seadatanet.org/) (1999–2008);

– gridded satellite altimetry data of the sea surface level at the L4 processing level, provided by the CMEMS marine forecast service (https://doi.org/10.48670/moi-00141);

– gridded satellite data of the Black Sea SST at the L4 processing level, provided by the CMEMS marine forecast service (https://doi.org/10.48670/moi-00160).

Three-dimensional sea temperature and salinity fields are reconstructed for assimilation into the model based on the joint analysis procedure for altimetry level anomalies and temperature and salinity profiles presented in [12]. As in the aforementioned study, the basic thermohaline stratification of the basin was determined within a given time range, but the averaging window reached a maximum value of 180 days based on a limited number of observations. Due to insufficient observations in certain years in the early 2000s, the basic stratification was calculated by interpolation using neighboring values.

Next, the depth-dependent coefficients of the direct regression between altimetric sea level values (processing level L4) within a given time window and the deviations of temperature and salinity observations from basic stratification were determined. These coefficients were then used to reconstruct three-dimensional arrays of pseudo-measurements of seawater temperature (Tobs) and salinity (Sobs).

Data assimilation was performed using the following hybrid procedure. In the main pycnocline layer, the temperature and salinity fields were relaxed to three-

[3] Large, W.G. and Yeager, S.G., 2004. *Diurnal to Decadal Global Forcing for Ocean and Sea-Ice Models: The Data Sets and Flux Climatologies*. USA, Colorado: National Center for Atmospheric Research, 105 p. https://doi.org/10.5065/D6KK98Q6

[4] Polonskii, V.F. and Ostroumova, L.P., 2012. [*Basic Hydrological Characteristics of the Marine Estuaries of European Russia Rivers: A Database*]. State Certificate 2012620681 of Database Registration. Moscow: FSBI SOIN. (in Russian).

[5] Copernicus Marine Monitoring Service, 2016. *Global Ocean Physics Analysis and Forecast*. Mercator Ocean International. https://doi.org/10.48670/moi-00016

dimensional arrays of pseudo-measurements Tobs and Sobs over the entire depth for salinity and in the layer below 60 m for temperature. In the upper sea layer, satellite altimetry observations were assimilated using the procedure described in [9]. SST data assimilation was performed by correcting the heat flux in the upper layer [2].

CMEMS reanalysis (array 4). This Copernicus Marine Service product (*BLKSEA_MULTIYEAR_PHY*_007_004) represents the daily mean hydrodynamic fields in the Black Sea from 01.01.1993 to 30.06.2021, obtained through reanalysis. These fields were analyzed earlier in [3] for the time period up to the end of 2018. The hydrodynamic core of the reanalysis is based on the NEMO *v*4 ocean general circulation model configured for the Black Sea basin, with a horizontal resolution of 1/27° × 1/36° at 31 vertical levels. The atmospheric fields of the ERA-5 ECMWF system, which have a spatial resolution of 1/4° and a temporal resolution of 1 h, are applied as atmospheric forcing. In the current configuration, the Bosphorus Strait boundary is closed when calculating the reanalysis. Data assimilation was carried out on the basis of the 3DVAR variation scheme, for which the authors used the OceanVar program [13, 14]. During the reanalysis, they assimilated *in situ* temperature and salinity measurements from the SeaDataNet and CMEMS datasets, as well as satellite data tracking sea surface level anomalies (CMEMS).

Firstly, it should be noted that the main difference between arrays 3 and 4 lies in the data assimilation procedure. For array 3 reconstruction, we applied an original MHI-developed procedure, the essence of which is presented above. The versions of the models used and the parameters of the computational grids also differ. In addition, the MHI reanalysis (array 3) takes the Marmara Sea basin into account in the calculations, which should affect the characteristics of water exchange through the Bosphorus Strait. Due to the difference in size of the computational grid cells, it can be expected that the turbulent exchange coefficients and time step for the two reanalyses will also differ. However, the authors do not provide more detailed information when describing array 4.

Main trends in temperature and salinity field changes in the Black Sea in 2000–2020

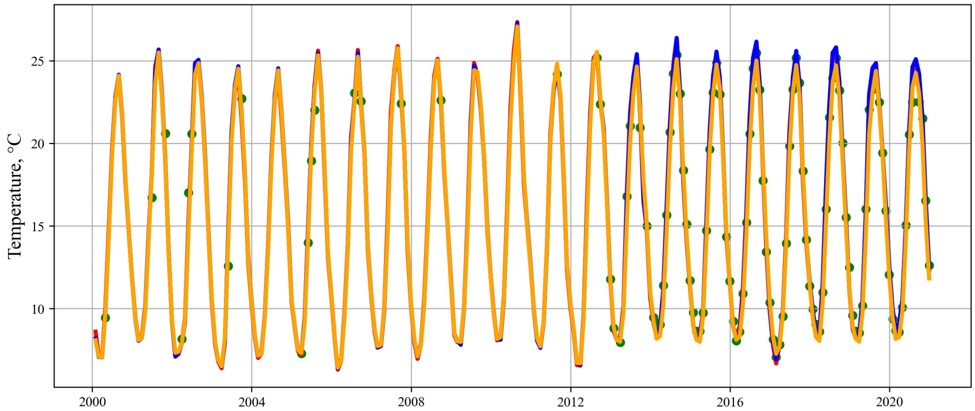
The prepared arrays of results from three reanalyses and observational data for individual months, when hydrological soundings more or less uniformly covered the area of the Black Sea, are used to analyze trends in temperature and salinity changes in seawater over the past 20 years. If significant discrepancies are observed in the reanalysis data under consideration, those close in at least two of the analyses are considered reliable. This approach is due to the fact that reanalyses performed on the basis of different models can produce noticeably different results [6] [15].

Trends in temperature field variation and the CIL structure. In [4], trends in upper layer heating in the Black Sea are examined through an analysis of changes in average temperature values at 60 m horizons near the CIL's minimum temperature

[6] IPCC, 2023. *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, 2392 p. https://doi.org/10.1017/9781009157896

and at 150 m, which is the main pycnocline's lower boundary, according to three reanalyses. This paper will mainly illustrate the warming process of the upper 200-meter layer of the Black Sea by examining the behavior of the CIL.

Fig. 2 shows the time evolution of the averaged temperature over the Black Sea basin at a 5 m horizon. The graph clearly shows the seasonal variation in surface temperature and interannual variability of its maximum and minimum values. At the same time, all reanalyses provide similar temperature change values.

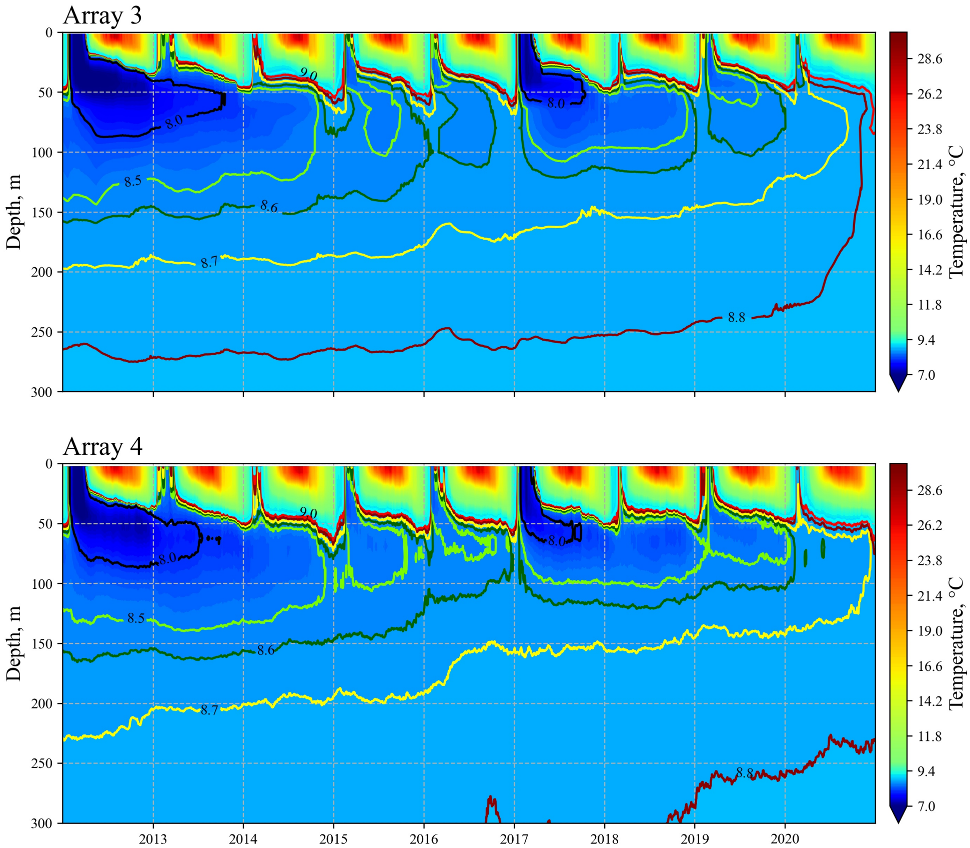


F i g. 2. Time evolution of the area-averaged temperature at the 5 m horizon obtained from three reanalyses. The red line corresponds to array 3, the blue line – to array 4, and the yellow line – to array 2. Green circles denote measurements

The similarity in the temperature time evolution at the 5 m horizon in different reanalyses is largely due to the fact that they all assimilate SST satellite observations. Therefore, the temperature evolution over time in the near-surface sea layer in the reanalyses is close to satellite SST (see Fig. 1 from [4]) and, consequently, to each other. Until 2012, there are quite a large number of minima of the average Black Sea near-surface temperature below 8 °C, after which there is a noticeable decrease. In [4], time diagrams showing changes in the average values of seawater temperature over horizontal sections are presented for all three reanalyses. Moreover, all reanalyses demonstrate areas of water limited by the 8°C isotherm, up until 2012, with brief interruptions. In addition, the renewal of CIL waters by cold surface waters in winter is clearly visible. After that, traditional CIL, which is limited by the 8 °C isotherm and ventilated during winter convection, is observed less frequently.

This paper considers the CIL behavior since 2012 in more detail, i.e. during the period of greatest heating of the upper layer of the Black Sea. According to Fig. 5 from [4], a linear regression constructed using observational data and all reanalyses demonstrates an increase in the temperature growth rate after 2012 for the time intervals 2000–2011 and 2012–2020. For the second time period, an almost twofold increase in the rate of seawater temperature growth is evident. Fig. 3 shows the diagrams of changes in the area-averaged horizon temperatures in the upper

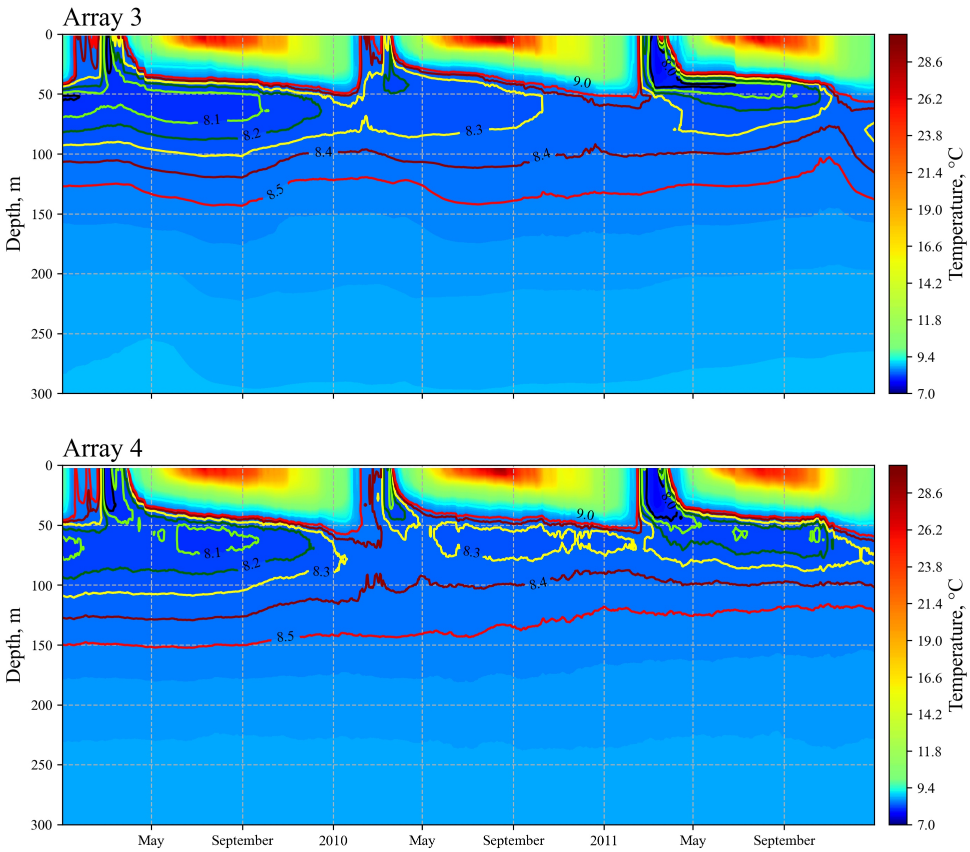
300-meter layer over time for data arrays 3 and 4. As shown in [4], array 2 provides slightly overestimated values of seawater temperature at the 60 m horizon, which approximately corresponds to the CIL core depth. It also fails to reconstruct the winter convection of 2017 (Fig. 3 from [4]). Meanwhile, arrays 3 and 4 demonstrate similar temperature changes during the time period under study.



F i g. 3. Time diagram of changes in sea water temperature average over the horizontal cross-sections in the Black Sea deep part for two reanalyses

A cold winter was observed in 2012. As a result of winter convection, the CIL was restored, reaching a core temperature below 8 °C. This temperature was maintained until around mid-2013. In contrast, the CIL core temperature had exceeded 8 °C for the previous three years (Fig. 4).

The traditional ventilated CIL remained after 2013, but the temperature values in its core increased to 8.5–8.6 °C. In 2017, a rather cold winter was observed in the Black Sea, with minimum near-surface temperature values below 8 °C (Fig. 2), similar to the conditions in winter 2004. The traditional ventilated CIL formed due to winter convection had a significantly smaller cold content than in 2004. The mass of cold water entering the CIL in 2017 further supported this layer, with temperature values in the core increasing to 8.6–8.7 °C by the end of 2018. The following year, 2019, saw a slight drop in the near-surface winter temperature below 8°C, while the CIL formed due to winter thermal convection had a seawater temperature of 8.5 °C in its core. This increased to 8.6 °C by the end of the year.

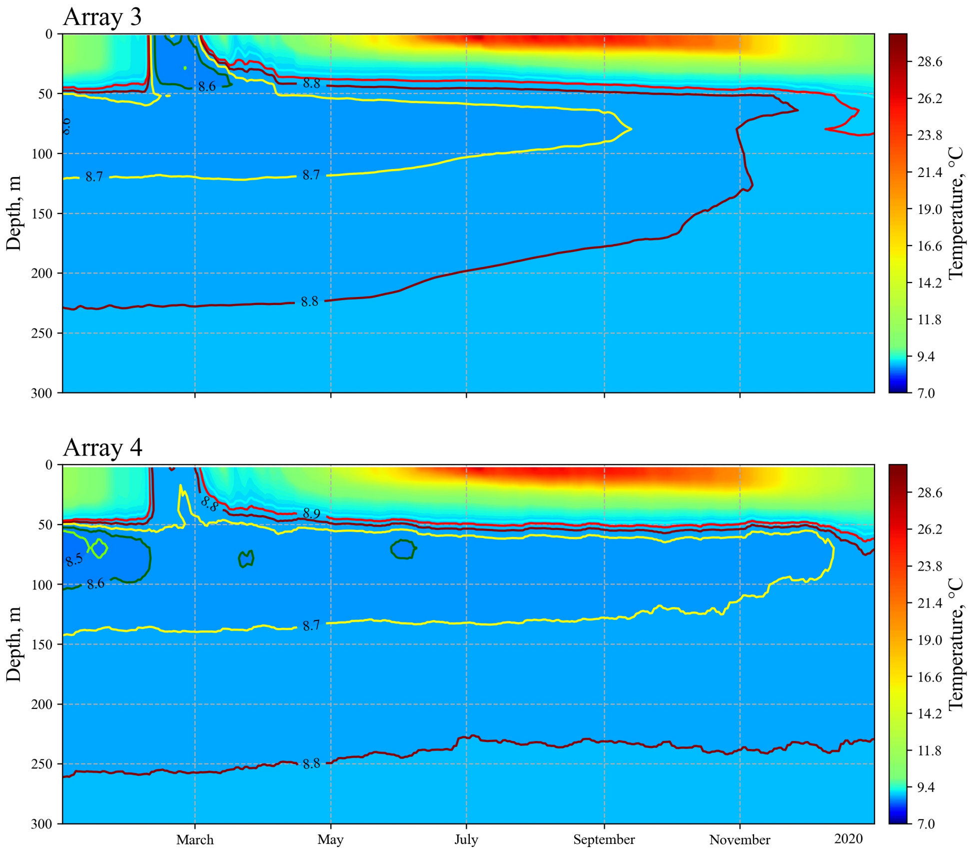


F i g. 4. The same as in Fig. 3, for 2009–2011

In 2020, winter thermal convection did not reach 50 m, meaning the traditional CIL, which is formed by the inflow of cold surface waters, was not renewed (Fig. 5). This phenomenon has never been observed throughout the history of oceanographic research in the Black Sea. However, according to data from arrays 3 and 4, a temperature minimum of ~ 8.7 °C is observed at a depth of ~ 75 m, and this layer is fundamentally different in nature to the traditional CIL, which is ventilated in winter. Its existence is solely due to the presence of warm waters with temperatures above 9 °C near the basin bottom.

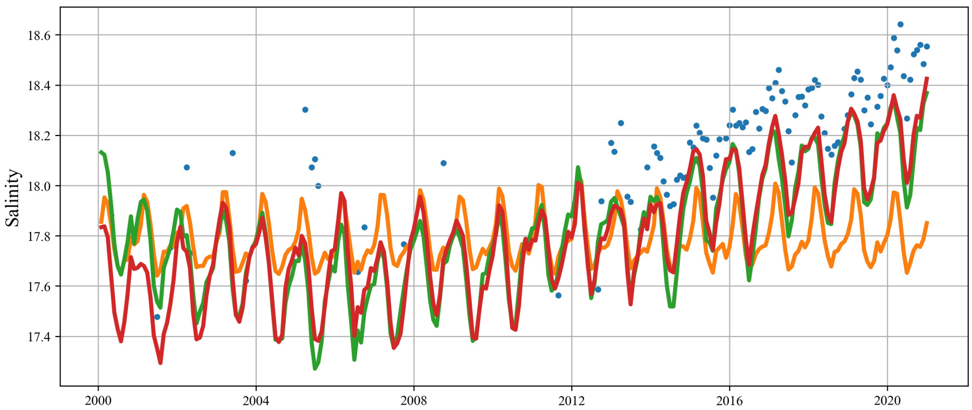
Trends in salinity field changes. Let us examine the trends in seawater salinity over the study period. Fig. 6 shows the temporal evolution plots of the spatially averaged salinity at a depth of 5 m in the deep-water part of the Black Sea. The figure clearly reveals an increasing salinity trend in the sea surface layer. Notably, the salinity of surface waters in the deep-water part of the basin was relatively low between 2000 and 2008, reaching an annual mean of ~ 17.6

in 2006–2007. The maximum freshening of the surface waters of the Black Sea, which was observed between 2005 and 2006, had previously been noted in observational data. However, the limited number of measurements made it difficult to provide reliable quantitative estimates of this state. Nevertheless, the water balance assessments in atmospheric reanalyses indirectly confirmed it. From 2008 onwards, surface salinity increased in both reanalysis arrays 3 and 4, as well as in the observational data, reaching 18.1–18.15 in 2019–2020. These changes in the Black Sea surface salinity align with an approximately 20-year cycle associated with fluctuations in the freshwater budget entering the Black Sea.

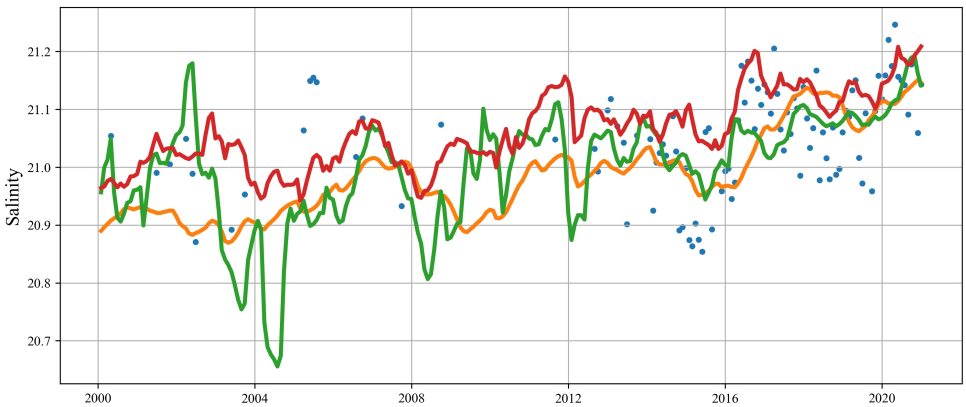


F i g. 5. The same as in Fig. 3, for 2020

Across all the reanalysis datasets presented in this study, an increase in seawater salinity of approximately 0.2 over 20 years has been observed at a depth of 150 m, which roughly corresponds to the lower boundary of the pycnocline (Fig. 7). Since the beginning of regular hydrological observations in the Black Sea [16], a continuous upward trend in both temperature and salinity has been recorded in the deeper layers of the main pycnocline. This trend emphasises the non-stationary nature of the basin's haline regime, which is linked to the inflow of warm, saline Mediterranean waters through the Bosporus Strait.



F i g. 6. Temporal evolution of monthly average values of seawater salinity at the 5 m horizon for each reanalysis and based on available observations. The red line corresponds to array 4, the green line – to array 3, and the yellow line – to array 2. Blue points denote measurement results



F i g. 7. The same as in Fig. 6, for the 150 m horizon

Conclusion

This study examines trends in changes to the hydrological regime of the Black Sea. The study is based on reanalysis data obtained through three different methods and, where possible, supplemented by direct observational data. Analysis revealed that, due to the increasing mean SST of the Black Sea waters (since 2005), the Black Sea Cold Intermediate Layer (CIL) is disappearing from its traditionally defined state as a subsurface water layer with temperatures ≤ 8 °C. Furthermore, accelerated warming of the sea within the main pycnocline has been observed. If these trends persist for 8–10 years, it could lead to significant changes in the vertical stratification of Black Sea waters, which would likely affect the basin's biological resources. Simultaneously, the haline regime of the sea is characterized by a transition from freshening to salinization of the surface layer in 2012–2015, associated with changes in the external freshwater budget and a long-term increase in salinity in the main pycnocline. Ultimately, we can expect an intensification of density stratification in the basin, as well as slowing of deep-water ventilation processes, due to the gradual, constant uplift of the main pycnocline and the warming of the surface layer.

REFERENCES

1. Polonskii, A.B. and Novikova, A.M., 2020. Interdecadal Variability of the Black Sea Cold Intermediate Layer and Its Causes. *Russian Meteorology and Hydrology*, 45(10), pp. 694-700. https://doi.org/10.3103/S1068373920100039
2. Belokopytov, V.N., 2011. Interannual Variations of the Renewal of Waters of the Cold Intermediate Layer in the Black Sea for the Last Decades. *Physical Oceanography*, 20(5), pp. 347-355. https://doi.org/10.1007/s11110-011-9090-x
3. Stanev, E.V., Peneva, E. and Chtirkova, B., 2019. Climate Change and Regional Ocean Water Mass Disappearance: Case of the Black Sea. *Journal of Geophysical Research: Oceans*, 124(7), pp. 4803-4819. https://doi.org/10.1029/2019JC015076
4. Korotaev, G.K., Belokopytov, V.N., Dorofeev, V.L., Mizyuk, A.I. and Kholod, A.L., 2024. Acceleration of Climate Change in the Upper Layer of the Black Sea. *Doklady Earth Sciences,* 518(1), pp. 1550-1555. https://doi.org/10.1134/S1028334X24602797
5. Grigor'ev, A.V., Ivanov, V.A. and Kapustina, N.A., 1996. Correlation Structure of the Black Sea Thermohaline Fields in the Summer Season. *Oceanology*, 36(3), pp. 334-339.
6. Polonskii, A.B. and Shokurova, I.G., 2008. Statistical Structure of the Large-Scale Fields of Temperature and Salinity in the Black Sea. *Physical Oceanography*, 18(1), pp. 38-51. https://doi.org/10.1007/s11110-008-9008-4
7. Demyshev, S.G. and Korotaev, G.K., 1992. [Numerical Energy-Balanced Model of the Baroclinic Currents in Ocean with Uneven Bottom on a C-Grid]. In: INM RAS, 1992. *Numerical Models and Results of Calibration Calculations of Currents in the Atlantic Ocean*. Moscow: Institute of Numerical Mathematics RAS, pp. 163-231 (in Russian).
8. Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R. [et al.], 2020. The ERA5 Global Reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), pp. 1999-2049. https://doi.org/10.1002/qj.3803
9. Dorofeev, V.L. and Sukhikh, L.I., 2016. Analysis of Variability of the Black Sea Hydrophysical Fields in 1993-2012 Based on the Reanalysis Results. *Physical Oceanography*, (1), pp. 33-47. https://doi.org/10.22449/1573-160X-2016-1-33-47
10. Dorofeev, V.L. and Korotaev, G.K., 2004. Assimilation of the Data of Satellite Altimetry in an Eddy-Resolving Model of Circulation of the Black Sea. *Physical Oceanography*, 14(1), pp. 42-56. https://doi.org/10.1023/B:POCE.0000025369.39845.c3
11. Mizyuk, A.I., Korotaev, G.K., Grigoriev, A.V., Puzina, O.S. and Lishaev, P.N., 2019. Long-Term Variability of Thermohaline Characteristics of the Azov Sea Based on the Numerical Eddy-Resolving Model. *Physical Oceanography*, 26(5), pp. 438-450. https://doi.org/10.22449/1573-160X-2019-5-438-450
12. Korotaev, G.K., Lishaev, P.N. and Knysh, V.V., 2016. Reconstruction of Three-Dimensional Fields of Temperature and Salinity Based on Satellite Altimetry. *Issledovanie Zemli iz Kosmosa*, (1-2), pp. 199-212. https://doi.org/10.7868/S0205961416010073 (in Russian).
13. Dobricic, S. and Pinardi, N., 2008. An Oceanographic Three-Dimensional Variational Data Assimilation Scheme. *Ocean Modelling*, 22(3-4), pp. 89-105. https://doi.org/10.1016/j.ocemod.2008.01.004
14. Storto, A., Dobricic, S.., Masina, S. and Di Pietro, P., 2011. Assimilating Along-Track Altimetric Observations through Local Hydrostatic Adjustment in a Global Ocean Variational Assimilation

System. *Monthly Weather Review*, 139(3), pp. 738-754. https://doi.org/10.1175/2010MWR3350.1

15. Balmaseda, M.A., Hernandez, F., Storto, A., Palmer, M.D., Alves, O., Shi, L., Smith, G.C., Toyoda, T., Valdivieso, M. [et al.], 2015. The Ocean Reanalyses Intercomparison Project (ORA-IP). *Journal of Operational Oceanography*, 8(1), pp. 80-97. https://doi.org/10.1080/1755876X.2015.1022329

16. Simonov, A.I. and Altman, E.N., eds., 1991. *Hydrometeorology and Hydrochemistry of Seas in the USSR. Vol. 4. Black Sea. Issue 1. Hydrometeorological Conditions.* Saint Petersburg: Gidrometeoizdat, 429 p. (in Russian).

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Artem I. Mizyuk – preparation of a regional configuration of the NEMO ocean dynamics numerical modeling complex; reanalysis based on it; participation in the discussion of the article materials and analysis of the results; participation in the text editing

Oksana S. Puzina – preparation of atmospheric impact for the NEMO ocean dynamics numerical modeling complex; conducting numerical experiments; participation in the analysis of the results

Anton L. Kholod – preparation of data from the CMEMS reanalysis array for research purposes; preparation of illustrative materials for the article; participation in discussion of materials; participation in analysis of results

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