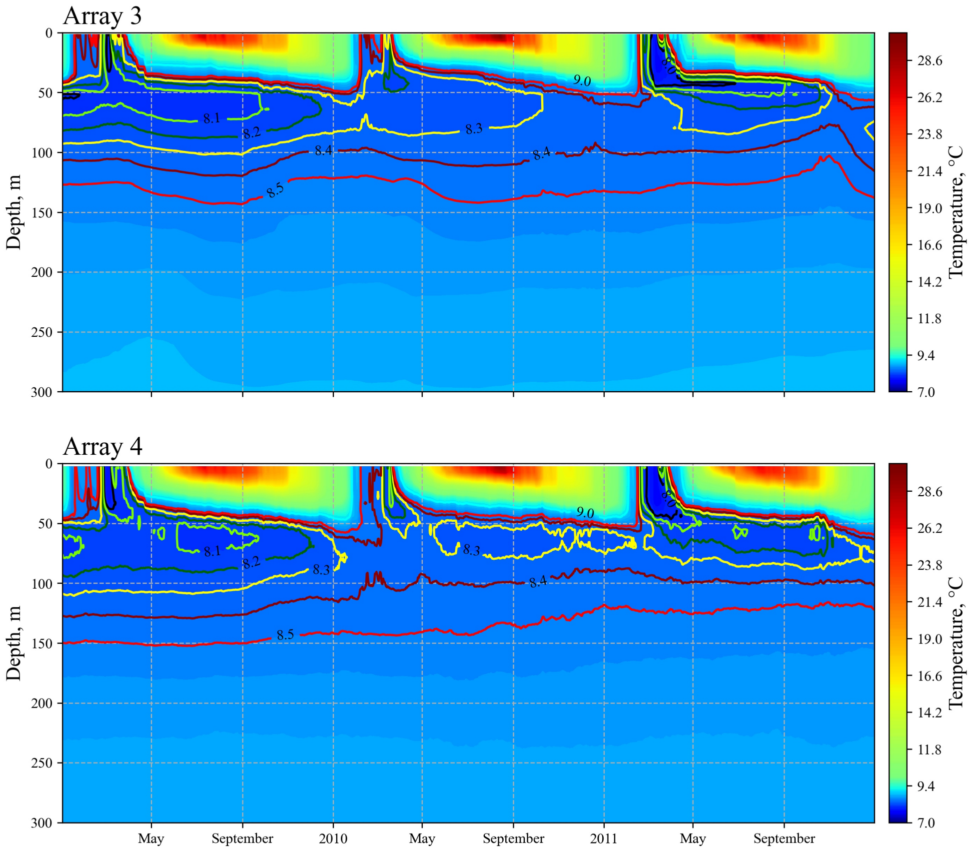
300-meter layer over time for data arrays 3 and 4. As shown in [4], array 2 provides slightly overestimated values of seawater temperature at the 60 m horizon, which approximately corresponds to the CIL core depth. It also fails to reconstruct the winter convection of 2017 (Fig. 3 from [4]). Meanwhile,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

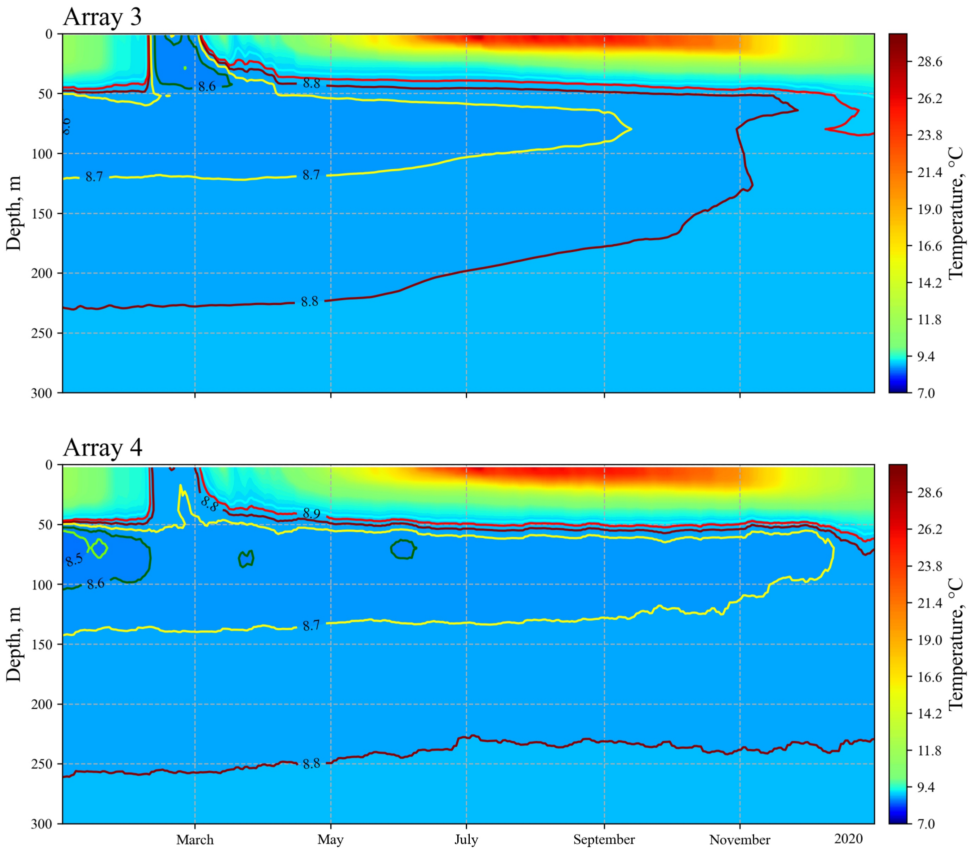


F i g. 4. The same as in Fig. 3, for 2009–2011

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.

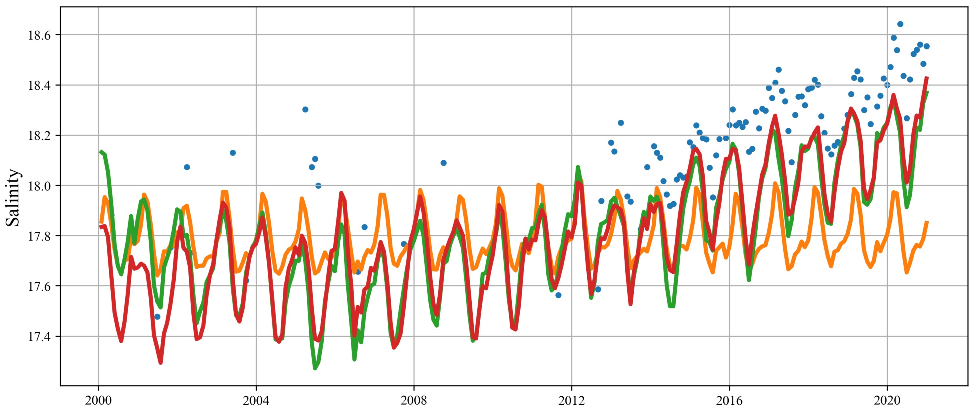
Trends in salinity field changes. Let us examine the trends in seawater salinity over the study period. Fig. 6 shows the temporal evolution plots of the spatially averaged salinity at a depth of 5 m in the deep-water part of the Black Sea. The figure clearly reveals an increasing salinity trend in the 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.

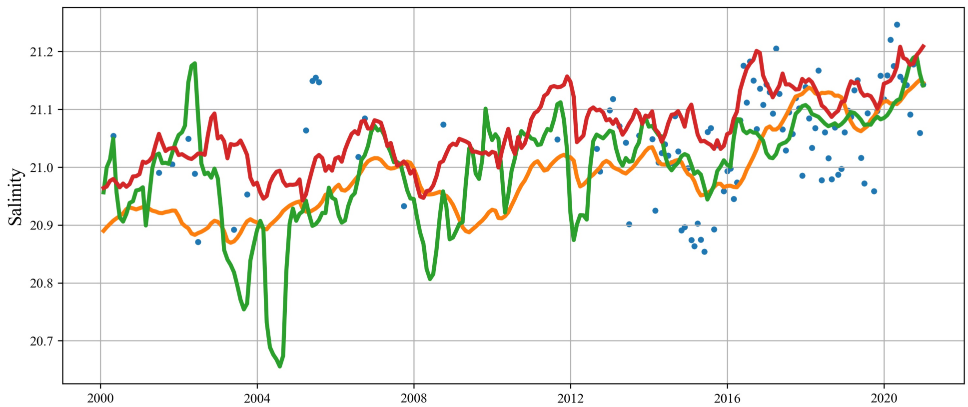


F i g. 5. The same as in Fig. 3, for 2020

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.

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Viktor L. Dorofeev – reanalysis based on the MHI Black Sea circulation model; participation in the discussion of the article materials; participation in the analysis of the results; preparation of the article text; text editing and refinement

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

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