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Original article

Evolution of Cold Intermediate Layer of the Black Sea in 2000–2021

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Abstract
Purpose. The purpose of the work is to study the spatiotemporal evolution of the cold intermediate layer in the deep part of the Black Sea in 2000–2021.
Methods and Results. The processes of formation of the cold intermediate layer in the Black Sea and its temporal evolution during 2000–2021 are studied based on the integrated application of satellite measurements of sea surface temperature, measurements from Argo floats, and two reanalyses providing regular three-dimensional temperature fields. Within the period under study, four stages of evolution were identified. During the first stage, from 2000 to 2005, the cold intermediate layer was close to the climatological norm, was actively renewed by winter convection, occupied the entire deep part of the sea and remained continuous almost until the end of the year. In 2006–2011 (the second stage), powerful ventilation in 2006 was followed by warm winters that induced the erosion of the cold intermediate layer off the southern and eastern coasts, its fragmentation and a reduction in its cold content. During the third stage (2012–2016), the cold intermediate layer was temporarily restored due to the cold winter of 2012, but during the subsequent warm years it became seasonal, disappearing completely by late summer. During the fourth stage (2017–2021), even after the cold winter of 2017, the cold intermediate layer moved closer to the surface, which accelerated its degradation, and by 2020 the layer with a core temperature below 8 °C had completely disappeared.
Conclusions. During the period from 2000 to 2021, the classical cold intermediate layer of the Black Sea, with a core temperature below 8 °C, underwent significant degradation, culminating in its complete disappearance by 2020. The main reason for its degradation is regional climate change, which is characterised by an increase in the frequency of warm winter periods and a reduction in the intensity and duration of winter convection. The acceleration of the cold intermediate layer degradation is also related to the rise of its core towards the surface, a decrease in its vertical extent, disruption of its continuity, and increased horizontal mixing by large-scale currents. The results obtained from reanalysis data are consistent with field observations and confirm the tendency for the cold intermediate layer to lose its classical defining characteristic, namely the presence of the 8 °C isotherm. This fact indicates a significant restructuring of the thermal structure of the Black Sea.

Keywords: cold intermediate layer, Black Sea, temperature, evolution, vertical structure, retrospective analysis, numerical modeling, field measurements

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Introduction

Recent observations convincingly demonstrate a substantial transformation of the vertical thermal structure of the Black Sea [1]. The most significant changes affect the cold intermediate layer (CIL) – a specific water mass formed mainly through ventilation of the upper layers of the sea during winter convection and becoming isolated from the surface layer during spring warming. As a result of regional warming over recent decades, the CIL, which had been consistently observed in all seasons for more than a century of instrumental measurements, has noticeably degraded.

Gradual CIL degradation was identified from observational data [2–5] and modeling results [6–9]. An analysis of the overall evolution of this layer during 2000–2020 was also performed in [10, 11] using data from three reanalyses providing three-dimensional seawater temperature fields on a regular grid. The reanalysis data showed that until about 2012, a relatively slow increase in the CIL core temperature was observed, followed by accelerated warming. In [10, 11], only the area-averaged vertical temperature stratification was evaluated. However, reanalysis data allow a fairly detailed tracking of spatial changes in the CIL structure [6].

In the present work, data from two reanalyses are used to describe the characteristic changes in the spatial structure of the CIL during 2000–2021. Hereafter, the term CIL refers to the "traditional" water mass bounded by the 8 °C isotherms. Section 2 describes the observational and reanalysis datasets used. Section 3 provides a comparative characterisation of the datasets. Section 4 describes the features of the CIL formation and its temporal evolution during 2000–2021. The Conclusion section discusses general patterns of the CIL formation in relation to winter atmospheric conditions, its spatial distribution across the Black Sea basin, and its degradation over time.

The purpose of this work is to conduct a comprehensive analysis of the long-term dynamics of the Black Sea cold intermediate layer, including its spatial structure, renewal periods, and progressive degradation, based on reanalysis data and measurements from Argo profiling floats.

Data and methods

Changes in the CIL characteristics were assessed using satellite sea surface temperature (SST) data (the *SST_BS_SST_L4_REP_OBSERVATIONS_010_022* product from the Copernicus Marine Service (CMEMS)), vertical temperature profiles from Argo profiling floats, and the results from two reanalyses.

The reanalysis performed at Marine Hydrophysical Institute (MHI) of RAS is based on the NEMO model [1], which reproduces the dynamics and trends of hydrophysical parameters in the Azov, Black, and Marmara seas [12]. The computational grid of the regional configuration of the NEMO v.3.6 ocean dynamics modeling system covers these basins with a horizontal grid spacing of 1/17° × 1/24°. The model assimilates three-dimensional temperature and salinity fields reconstructed from satellite altimetry and satellite SST data using a technique

[1] Madec, G., 2008. *NEMO Ocean Engine*. Note du Pôle de Modélisation, No. 27. Paris: Institut Pierre-Simon Laplace (IPSL), 300 p.

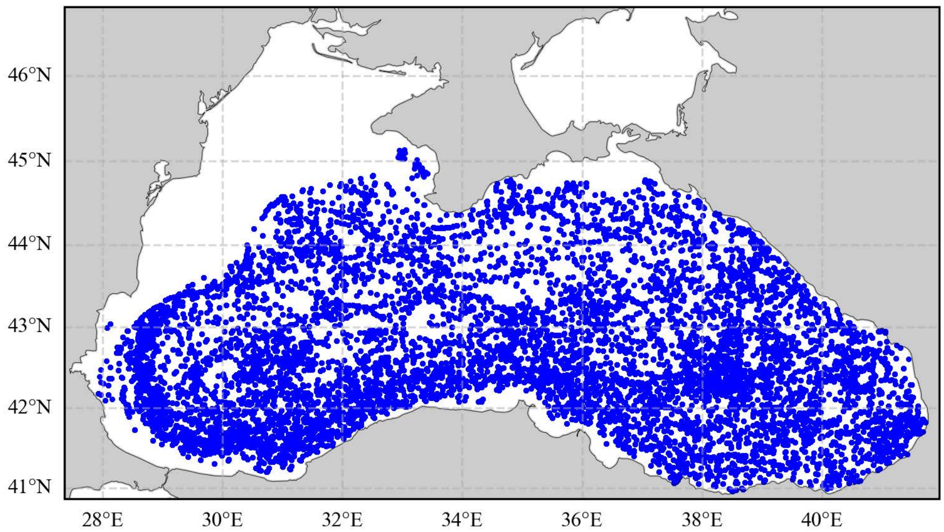
close to that described in [8]. A more detailed description of the reanalysis procedure is given in [11].

The *BLKSEA_MULTIYEAR_PHY_007_004* product from CMEMS provides daily mean hydrodynamic fields for the Black Sea from 1 January 1993 to 30 June 2021. The hydrodynamic core of this reanalysis is based on the NEMO v.4 general ocean circulation model, with a horizontal resolution of 1/27° × 1/36°. Data assimilation was performed using a 3DVAR variational scheme [13, 14]. The reanalysis assimilated *in situ* temperature and salinity measurements from SeaDataNet and CMEMS datasets, as well as satellite along-track sea level anomalies from CMEMS. A detailed description of the CMEMS reanalysis algorithm is also given in [11].

Accuracy characteristics of the datasets used

Satellite SST data have a root-mean-square error (RMSE) of about 0.5 °C relative to *in situ* measurements. Estimating the actual accuracy of temperature measurements obtained from Argo floats is rather difficult because measurement drift may occur due to the lack of regular calibration. More recent measurements were presumably more stable. In this work, we neglect the errors in seawater temperature measurements obtained from profiling floats.

Argo float data have been available since 2005. The number of floats in the Black Sea varied over the years, and they were usually unevenly distributed across the basin. Fig. 1 shows that the density of Argo soundings is higher in the southwestern part of the basin and in its southern part, along the Anatolian coast (the Asia Minor Peninsula).



F i g. 1. Distribution of the *Argo* float soundings in the Black Sea in 2005–2021

This distribution is partly explained by the fact that the floats were deployed in the southwestern corner of the basin and then carried along the coast by the Rim Current (RC). A higher sounding density is also observed in the eastern part of the basin, within a limited area around 42.2°N, 38.1°E, apparently due to the interaction between the RC and the Batumi Eddy. The relatively small number of measurements per year and their uneven spatial distribution hinder the analysis of CIL changes based solely on float data [4].

The advantage of reanalyses is that they provide continuous representations of the spatiotemporal evolution of fields within a marine basin. However, the accuracy of the reconstruction of temperature fields in reanalyses is significantly lower than that of instrumental observations. Since we are interested in changes occurring in the CIL, the accuracy of the reanalyses was assessed against all measurements obtained by floats in the Black Sea during 2005–2021 within the depth range of 40–100 m, i.e. where the upper and lower boundaries of the CIL are located.

The MHI reanalysis provides a mean deviation from instrumental measurements in this layer of −0.05 °C and an RMSE of 0.43 °C. For the CMEMS reanalysis, the mean deviation and RMSE are −0.04 °C and 0.30 °C, respectively. Note, however, that the accuracy of the CMEMS reanalysis may be somewhat overestimated because the float data used for the evaluation were already assimilated into the reanalysis.

Using data from both reanalyses, maps of cold content were constructed – a conditional quantity proportional to the volume of cold water and its temperature deviation from 8 °C. The cold content was calculated for the deep part of the sea at each model grid point using the formula

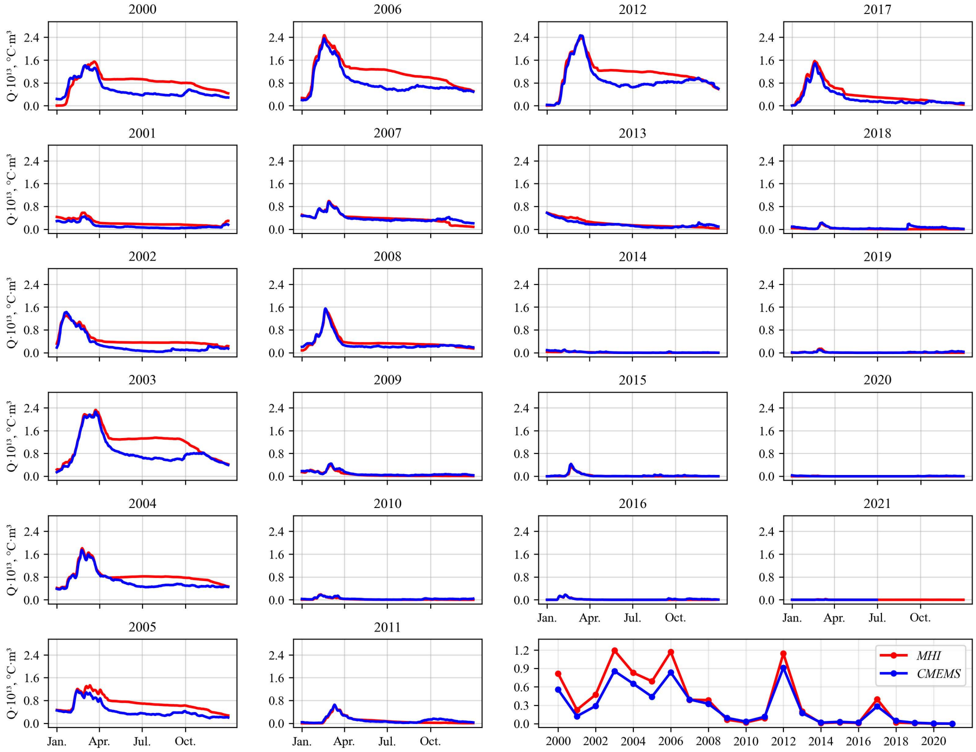
$$Q = \int (8\ °\mathrm{C} - T) dz,$$

where integration is carried out over the CIL depth range. Note that in winter, when convection develops in the sea, the upper boundary of the CIL may coincide with the sea surface in some areas in both the reanalysis data and float observations. Therefore, the constructed maps reflect the CIL cold content only after the CIL has been separated from the surface by warmer water as a result of surface warming.

The quality of the reanalysis data used for cold content mapping was assessed by comparison with Argo float observations. A total of 7108 temperature profiles were analysed to determine the presence or absence of water with a temperature below 8 °C. The MHI reanalysis indicated the absence of water below 8 °C in 334 cases where the floats indicated its presence; in 6447 cases, the reanalysis agreed with the float data; and in 327 cases, the reanalysis showed the presence of water below 8 °C, whereas the floats showed its absence. The CMEMS reanalysis indicated the absence of such water in 344 cases where the floats showed its presence, agreement in 6578 cases, and its presence in 186 cases where the floats showed its absence. Thus, overall, there is satisfactory agreement between the reanalysis data and observations.

The agreement between the reanalysis results is illustrated by the time series of the integral daily mean cold content in the deep part of the sea (Fig. 2).

The largest discrepancies between the estimates occur in years when only a small number of floats were operating in the sea. In particular, differences between the cold content estimates from the MHI and CMEMS reanalyses in the early 2000s are due to the fact that, prior 2005, there were no Argo observations in the open sea, and measurement data were not assimilated into the CMEMS reanalysis, whereas the MHI assimilation technique could assimilate data based solely on satellite observations. Where discrepancies occur, the MHI reanalysis provides higher cold content values than CMEMS, as shown in Fig. 2. After 2014, the number of floats increased, and the curves from the MHI and CMEMS reanalyses converge.



F i g. 2. Changes in the integral daily average CIL cold content for each year and its annual average values based on the results of MHI and CMEMS reanalyses

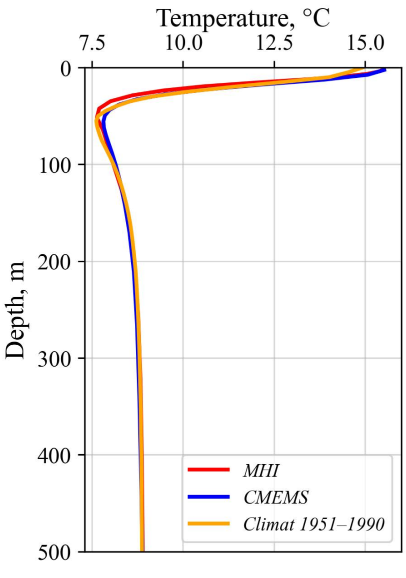
The observed discrepancies in cold content are partly related to the temperature threshold of 8 °C chosen to define the CIL. As shown by the analysis, in most cases, the CMEMS reanalysis indicates water temperatures 0.1–0.2 °C above 8 °C in areas where the MHI reanalysis gives temperatures below 8 °C. Therefore, the differences between the curves in Fig. 2 can be considered minor. For consistency, and because the MHI assimilation technique is less sensitive to the number of Argo observations, the subsequent analysis is based on estimates from the MHI reanalysis.

CIL formation and its temporal evolution

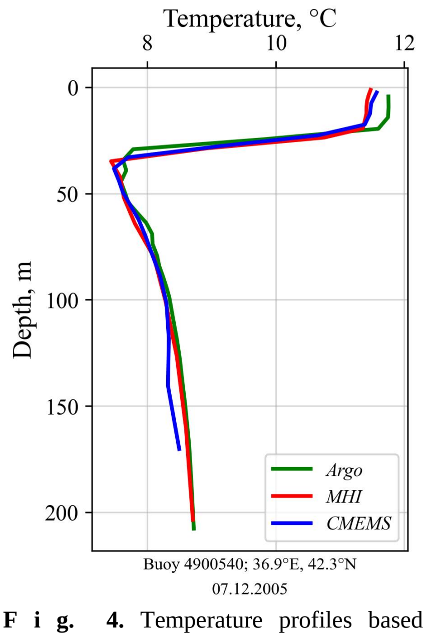
The temporal evolution of the CIL cold content in the deep part of the basin throughout the year differs between the convection period and the subsequent period, when the cold water is separated from the surface as the SST rises. An analysis of satellite SST maps on which the 8 °C isotherm was highlighted during the study period indicates that the surface water with an SST below 8 °C usually first appears in mid-January, initially on the northwestern shelf and in the form of a jet along the western shallow waters extending to the Bosphorus outlet. In the deep part of the basin, according to reanalysis data, cold water at the sea surface typically appears first in the west and then spreads eastward over time. In some years, a cold-water patch appears simultaneously in the centre or the northeastern part of the sea. Satellite observations show that after winter ends, water with an SST above 8 °C advances from east to west, separating the CIL from the sea surface. Note that complete separation of the CIL from the surface corresponds to a transition from rapid to slower temporal variations in the integral cold content (Fig. 2). This transition occurs mainly in March but sometimes extends until the end of April.

Four periods of CIL evolution can also be distinguished in Fig. 2: the first – from 2000 to 2005 (first column), the second – from 2006 to 2011 (second column), the third – from 2012 to 2016 (third column), and the fourth – from 2017 to 2021 (fourth column). Each of the second, third, and fourth periods is characterised by CIL renewal at the beginning of the cycle due to a cold winter, followed by degradation of the layer. The evolution of the CIL during each period is considered below.

From 2000 to 2005, except for 2001, relatively cold winters were observed in the Black Sea region, during which SST was below 8 °C across a significant part of the sea surface. Except for 2001, on certain winter days, water with an SST below 8 °C was observed throughout the deep part of the sea. The cold content of the CIL formed after the end of winter convection was approximately $0.5 \cdot 10^{13}$ °C·m^3 or higher. The mean vertical temperature profile derived from reanalysis data for 2000–2005 is close to the climatological profile for 1951–1990 (Fig. 3). This climatological profile was calculated for the deep part of the Black Sea based on the climatological dataset compiled using the method described in [15].



F i g. 3. Average vertical temperature profiles based on MHI and CMEMS reanalysis data for 2000–2005 and climate data for 1951–1990



F i g. 4. Temperature profiles based on reanalysis and Argo float data for 2005

Variations in cold content during 2000–2005 are explained by differences in the intensity of winter cooling. For example, the winter of 2001 was relatively mild: cold water with an SST below 8 °C appeared in mid-January only as a patch in the centre of the basin and remained confined to that part of the sea until the last ten days of February. During the last ten days of February, cold water with an SST below 8 °C spread eastwards to about 38°E and persisted, despite periodic reductions in its extent, until the end of March. By mid-April, the CIL occupied almost the entire sea area. The CIL cold content remained at about $2 \cdot 10^{12}$ °C·m^3 until the end of October 2001. Afterwards, however, the layer began to warm and, by the end of the year, partially lost its continuity. Nevertheless, December 2001 was quite cold. By 20 December, cold water and the convection zone occupied not only the northwestern shelf and the shallow waters along the western coast but also the central part of the sea. The cold-water zone with an SST below 8 °C expanded, and by mid-January, warmer water remained only in a strip along the Caucasian coast and the southern coast of Crimea.

This pattern persisted until the end of January 2002, but then, as the RC intensified in winter, warmer water had spread as far as the Anatolian coast by mid-February. The area of surface cold water gradually shrank, and in early April, the CIL was completely separated from the surface, occupying the entire deep part of the Black Sea. The continuous CIL in the deep part persisted until the last ten days of December 2002 and then began to erode off the Anatolian and Crimean coasts. At the same time, cold water accumulated in the centres of the eastern and western gyres and subsequently entered the CIL, as described in [16]. By the end of January 2003, warm water remained only in the eastern part of the sea and off the Crimean coast.

The winter of 2003 was prolonged, and by 20 March, an SST below 8 °C was observed over the entire sea surface. A substantial reduction in the cold-water surface area and the final separation of the CIL began only during the middle ten days of April 2003. A characteristic feature of the renewed CIL was the accumulation of water with temperatures below 8 °C in the cores of quasi-stationary anticyclones and near the coasts.

During May–July, the cold content of the CIL, which occupied the entire deep part of the sea, continued to grow due to the subduction of cold water from the shallow waters. The continuity of the CIL was maintained until the end of December 2003, but its cold content began to decrease at the end of July. From the last ten days of December 2003 and until the last ten days of January 2004, slight erosion of the CIL occurred off the Anatolian coast.

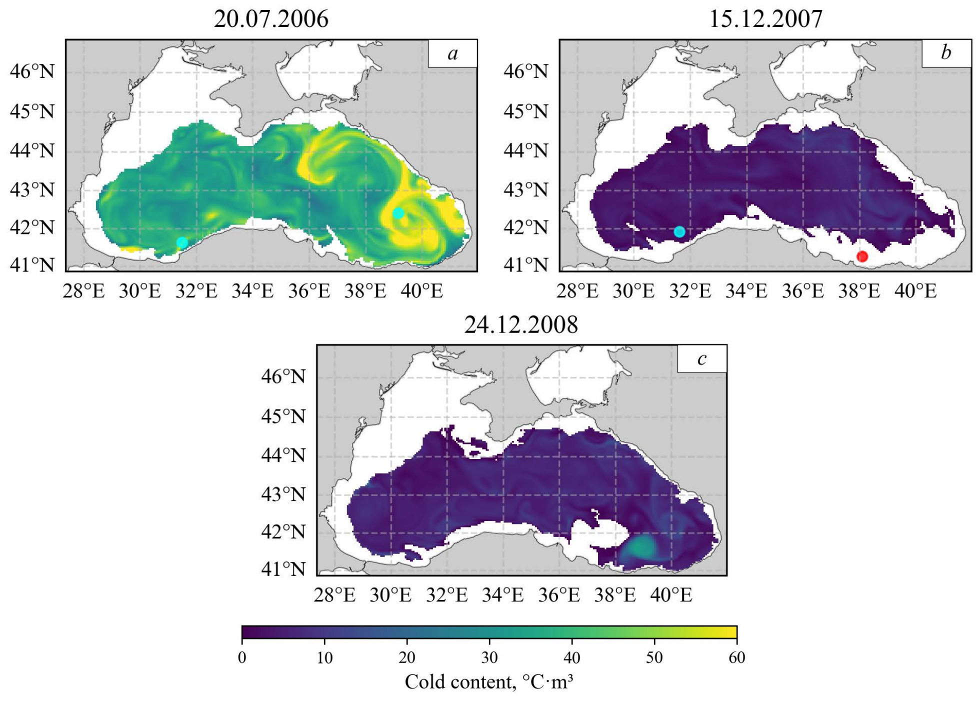
In 2004, an SST below 8 °C was observed over a significant part of the sea from about 10 February and persisted, with short warming spells, until the middle ten days of March. By the end of March, complete separation of the CIL had occurred, and until mid-October, it occupied the entire deep part of the sea. Then slight erosion began, but the layer largely retained its continuity until the subsequent cooling period. In December 2004, cold water accumulated only on the northwestern shelf and began to spread southwards along the western shallows. By the end of January 2005, the cold-water area had expanded eastwards. From about 10 February, water with an SST below 8 °C occupied the entire western half of the sea and approximately half of the eastern part, except for a strip of warmer water along the Caucasian coast.

At the end of March 2005, a cold spell occurred, and water with an SST below 8 °C covered the entire sea surface. As a result, the CIL became completely separated from the surface throughout the deep part of the sea during the middle ten days of April. The continuous CIL persisted until the end of November 2005, remaining clearly identifiable in the reanalysis data and float observations (Fig. 4).

At the beginning of the second period, the first half of January 2006 was warm, and SST everywhere exceeded 8 °C. From mid-January, water with an SST below 8 °C advanced from west to east. From early February to the end of March, water with an SST above 8 °C was confined to a narrow strip along the Caucasian coast.

By mid-April, the CIL was separated from the surface throughout the deep part of the sea. The integral cold content after CIL renewal during the prolonged convection in 2006 reached values comparable to those observed in 2003. Subsequently, the CIL maintained its continuity, with elevated cold content near the coasts and in anticyclones. Note that a significant volume of cold water in the CIL along the Anatolian coast in February and March originated from the cold jet that flowed along the western coast of the Black Sea.

During the summer, intense intrusions of CIL waters from the coast into the central part of the basin occurred (Fig. 5, *a*). These intrusions and the subsequent mixing homogenised the CIL within the deep part of the basin. As a result, from mid-July, the CIL warmed, and its cold content decreased.

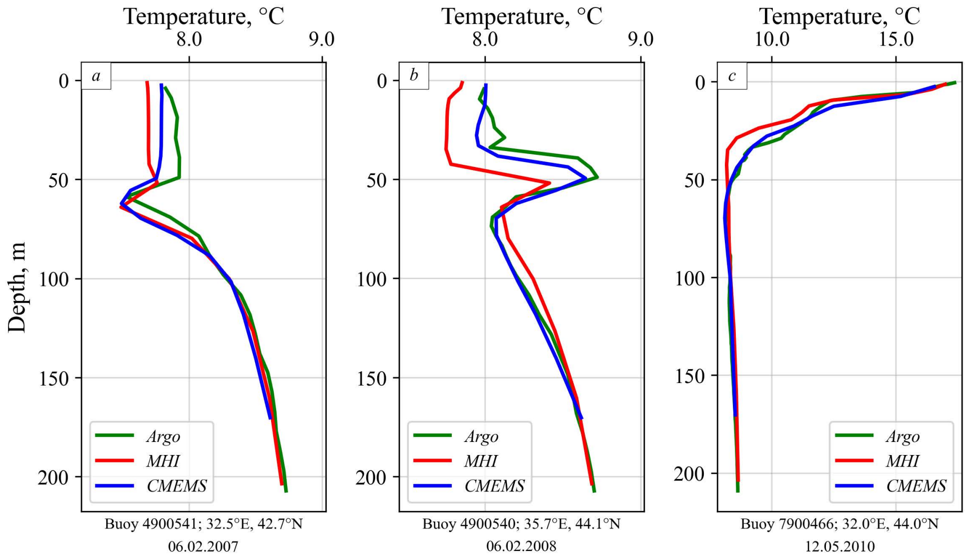


F i g. 5. CIL cold content based on MHI reanalysis data for 2006, 2007, and 2008. Position of Argo floats are shown by dots: the buoys which recorded CIL due to the measurement results are highlighted in blue, and the buoys with no records of CIL – in red

From mid-November, the CIL cold content began to decrease much faster due to the erosion of the layer off the Anatolian coast. Despite December 2006 being warm, the CIL remained continuous throughout the month.

During most of February, water with an SST above 8 °C persisted along the Anatolian, Caucasian, and Crimean coasts. Even where SST fell below 8 °C, convection did not reach the CIL core, so no renewal occurred (Fig. 6, *a*). By the end of February, warm surface water remained only in the southeastern corner, and there the CIL was not renewed by convection there. By the end of March, warm surface water occupied almost the entire deep part of the sea, and in April, complete separation of the CIL from the surface occurred.

After separation from the surface in April, the CIL was nearly continuous. Owing to the relatively warm winter, its cold content after the convection period was comparable to that observed in 2002 but noticeably lower than in 2003–2006. Note also that the contrast between the cold content density near the southern coast and that in the open sea was smaller than in some previous years.



F i g. 6. Temperature profiles based on reanalysis and Argo float data for 2007, 2008, and 2010

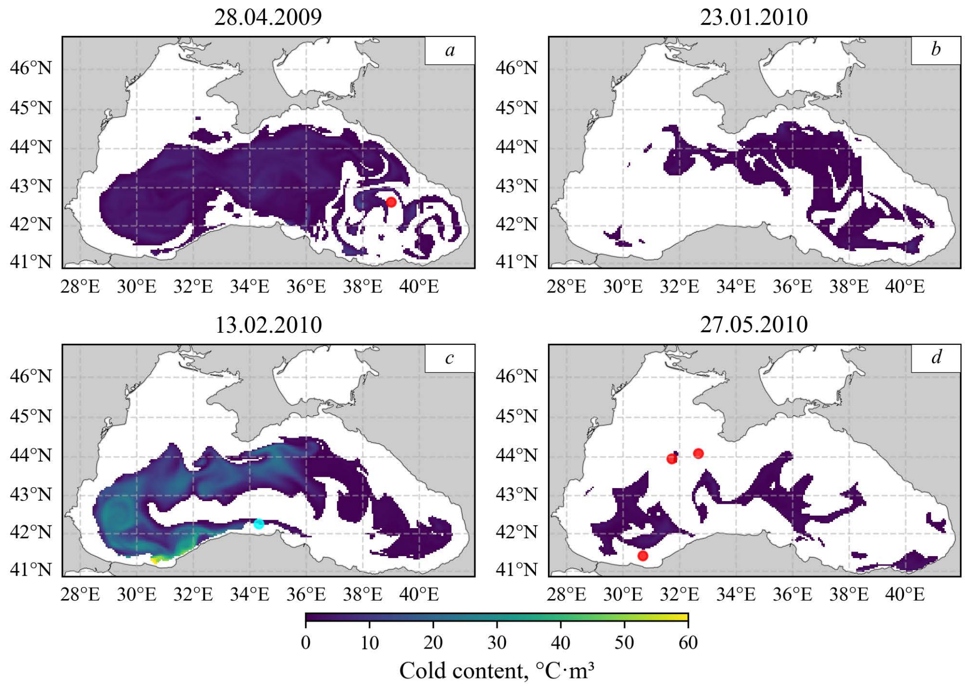
Despite the substantial reduction in cold content, the CIL retained its continuity throughout the summer. It was clearly identifiable, with a core temperature of around 7.5 °C. Slight erosion of the CIL began only in October, spreading westwards along the Anatolian coast and reaching the Caucasian coast in December (Fig. 5, *b*). In December 2007, water with an SST below 8 °C was observed only along the western coast of the sea and had extended eastwards beyond the Bosphorus outlet by the end of the month. As a result, the CIL cold content decreased noticeably by the end of the month (Fig. 2).

In January 2008, atmospheric conditions over the Black Sea were variable, so the area occupied by water with an SST below 8 °C changed constantly. Only by the end of the month did cold water occupy almost the entire sea surface, except for a narrow strip extending along the Caucasian and Crimean coasts and over the continental slope of the northwestern shelf, and continuing southwards along the western coast within the RC jet. By mid-February, water with an SST below 8 °C occupied almost the entire sea surface; by the end of March, a strip of such water remained only near the western coast.

According to the calculated vertical temperature distributions, from the end of January onwards, the convection zone in which CIL renewal occurred occupied most of the deep part of the sea. However, in a broad strip along the Caucasian coast, the CIL was absent. Note also the formation of atypical temperature profiles with a warm layer overlying the CIL off the Crimean coast and over the continental slope of the northwestern shelf (Fig. 6, *b*), apparently due to relatively weak convective mixing.

SST maps indicate that, by the end of February 2008, the entire surface of the deep part of the sea was affected by convection, but, according to Fig. 2, weak CIL renewal occurred only during the middle ten days of the month.

By about 10 March, the CIL was completely separated from the sea surface, occupying the entire deep part of the basin. At the same time, according to the calculated seawater temperature profiles, the CIL core over a significant part of the basin was located at depths shallower than 50 m, and its thickness was about 10 m. The proximity of the CIL core to the surface and its limited thickness led to episodic erosion at the margins of the deep basin as early as March. Meanwhile, a thick CIL, confirmed by float measurements, was observed in the region of the Batumi Anticyclone. The cold content in April reached a plateau at a value slightly lower than in 2007. It remained at this level until October 2008 (Fig. 2). Consequently, the CIL remained nearly continuous until about 10 October, with minor episodes of disruption. In December 2008, cold water with an SST below 8 °C was observed only on the northwestern shelf and along the western shallows. For this reason, CIL erosion became more widespread (Fig. 5, *c*).



F i g. 7. CIL cold content based on MHI reanalysis data for 2009 and 2010. Float positions are shown by dots (see Fig. 5 for an explanation

In January 2009, cooling occurred, and cold surface water began to appear in the centre of the sea as transient patches. Since warm surface water occupied the eastern part of the sea and the area along the Anatolian coast, CIL erosion continued there. This trend continued until the last ten days of February. Then the cold-water area extended as far as 38°E, but in the eastern and southeastern parts of the sea, where relatively warm water was at the surface, the CIL was absent. Thereafter, the cold surface-water area periodically contracted, and only on certain days in March did it occupy a substantial portion of the deep part of the basin; consequently, the CIL was absent from almost the entire periphery of this area. By the end of March, cold surface water remained only along the western coast as far as Burgas, and the CIL renewal period ended. Due to weak convection, the integral CIL cold content by April 2009 was substantially reduced compared with previous years (Fig. 2). CIL erosion intensified, particularly in the eastern part of the basin, where intense horizontal mixing occurred (Fig. 7, *a*).

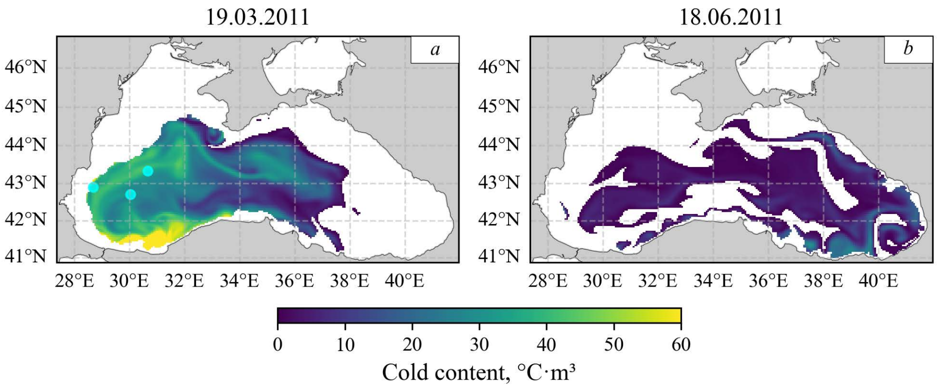
In May 2009, the area occupied by the CIL continued to shrink. By the end of May, the layer was absent throughout the region east of the Sinop–Poti section but still existed as a single continuous area in the western and central parts of the sea until the end of June. In July–August, the total CIL area changed little, but the configuration of its main area became increasingly fragmented. As a result, the rate of CIL warming increased, leading to a reduction in its integral cold content. Between late September and early October, the CIL underwent further fragmentation, but its area and cold content remained approximately constant until December. In December, two additional floats were present in the western part of the sea, and their measurement data, together with data from the float in the eastern part, confirmed the spatial configuration of the CIL. The cold content decreased substantially between early April and the end of December 2009, reaching a minimum.

The year 2010 began with unusually warm weather. Throughout the deep part of the sea, SST remained above 8 °C until 21 January. Cold water was confined to the western coast and did not quite reach the Bosphorus outlet. As a result, the pre-existing CIL persisted throughout the deep part of the sea until about 25 January, retaining the same configuration and area as in December (Fig. 7, *b*). After 21 January, the cold-water area began to spread eastwards, reaching about 30°E by 26 January, and an almost circular patch of water with an SST below 8 °C and a radius of about 50 km appeared in the northern part of the eastern gyre, south of eastern Crimea.

By the end of January, the cold surface-water area, about 100 km wide, extended eastwards into the centre of the sea. By about 10 February, it had expanded southwards to the Anatolian coast, advancing eastwards to 34°E. At the same time, the warm-water area, previously concentrated in the northern part of the eastern gyre, spread as far as the southern coast of the Black Sea. A sharp colour gradient at the longitude of the Kerch Strait on the cold content map for February 2010 (Fig. 7, *c*) separates the pre-existing CIL area in the east from the convection zone reaching the CIL core in the west. The figure shows that the cold water transported along the western coast of the sea reached the Anatolian coast by mid-February. Reanalysis data and direct measurements from a profiling float drifting in that area show that water with temperatures below 8 °C extended to depths of about 90 m. The formation of such a deep cold-water layer off the Anatolian coast may be partly related to the winter deepening of the pycnocline near the coast, caused by an intensified cyclonic wind stress curl over the sea during the winter season [17].

During the last ten days of February, cold water at the sea surface was concentrated in the west and centre of the basin and separated from the western coast by a "tongue" of warmer water transported by the RC. The area of cold surface water with an SST below 8 °C changed rapidly until about 20 March, at times fragmenting into small patches and at others merging into a single continuous area. As a result, convection alternately strengthened and weakened, and the CIL was ventilated only in some areas, periodically separating from the surface. By the end of March, cold surface water remained only near the western boundary of the basin, and the CIL was completely separated from the surface throughout the deep part of the basin. The rapid temporal changes in the distribution of cold water on the sea surface show that convection in February–March 2010 ventilated the CIL only weakly. This led to a sharp reduction in the integral CIL cold content in April 2010 (Fig. 2). Moreover, according to observational and reanalysis data, step-like structures were present in the temperature profiles (Fig. 6, *c*), resulting from alternating cooling and warming phases.

In April, the area occupied by the CIL began to shrink. By the end of May, this area had eroded and become fragmented, as confirmed by Argo float observations (Fig. 7, *d*). By the end of June, only isolated CIL patches remained. All Argo floats collecting measurements in June were located outside the CIL zone, and the temperature measured in all profiles was above 8 °C. In July–November, the CIL area continued to decrease. By the end of November, only isolated patches of water with temperatures below 8 °C remained. In December 2010, warm weather prevailed over the entire sea except for the northern part of the northwestern shelf. Therefore, cold water formed only near the Dnieper–Bug Estuary and then spread southwards along the western boundary of the sea, reaching areas south of Varna by the end of December. Consequently, the spatial extent of the CIL decreased even further. By the end of December, the cold content was lower than in all previous years.

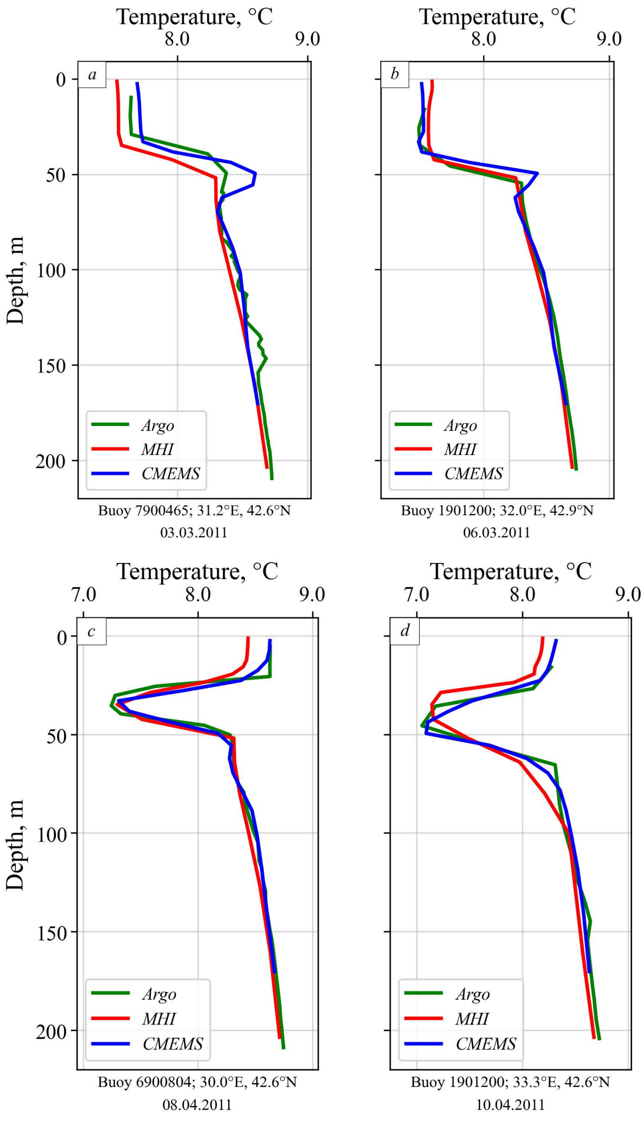


F i g. 8. CIL cold content based on MHI reanalysis data for 2011. Float positions are shown by dots (see Fig. 5 for an explanation)

In January 2011, warm weather persisted until the end of the month. Therefore, the area occupied by the CIL decreased substantially, and by the end of the month, the CIL remained only in the region of the Batumi Anticyclone. From 2 to

5 February, cold water intruded from the northwestern shelf into the deep part of the sea, spreading along the Anatolian coast. By mid-February, surface water with an SST below 8 °C began to spread eastwards, first in the centre of the sea and then, by about 20 February, across the entire width of the basin. By the end of February, the cold-water area had advanced to 34–35° E and reached 36–37° E in March; then the RC began transporting warm water westwards in the north and cold water eastwards in the south. Convection intensified in March in the western and central parts of the deep Black Sea, but did not intensify in the eastern part (Fig. 8, *a*).

However, even in the western part of the sea, convection remained shallow (Fig. 9, *a*, *b*). In places, the CIL began to separate from the surface. As a result, at the end of March, in the area of the warm surface water intrusion, a thin CIL was observed, with its core located at depths shallower than 50 m.



F i g. 9. Temperature profiles based on reanalysis and Argo float data for 2011

Relatively cold water at the sea surface persisted locally in the centre of the basin until mid-April 2011. However, the CIL in the deep part of the basin was already separated from the surface, remaining in the centre of the sea as a thin and narrow layer, as shown in Fig. 9, *c*. At the same time, towards the Anatolian coast, the CIL thickness increased (Fig. 9, *d*). The area occupied by this layer remained continuous, but the CIL did not extend over the entire deep part of the sea. Its cold content at the end of April reached the same level as in 2009.

In May, the CIL area extended eastwards, and its boundary became more irregular. In June, this area spread along the RC jets (Fig. 8, *b*). Subsequently, from July to October, it moved across the basin, becoming increasingly fragmented and slowly decreasing in area and cold content. In November, the reduction in area and cold content accelerated. As in 2010, only a few small CIL patches remained. By the end of December, the cold content slightly exceeded the 2010 level. The significant reduction in CIL area and cold content is explained by the shallow position and narrowness of the layer at the time of its separation from the sea surface, as well as by horizontal mixing, which increased the area of contact between cold water within the CIL and the surrounding warmer water.

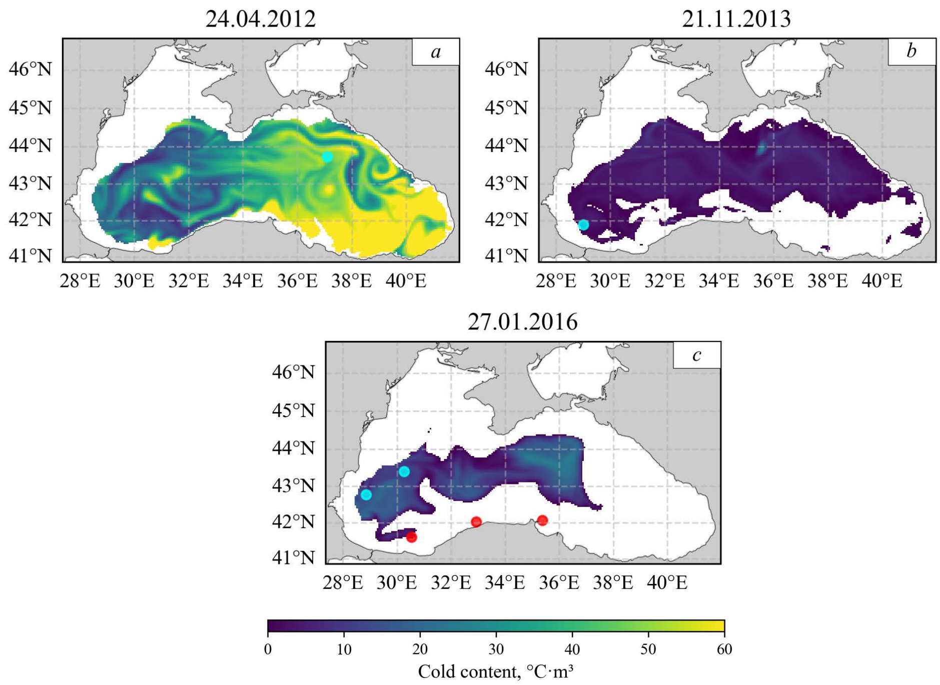
<u>The third period</u> began with warm weather during the first 20 days of January 2012. At that time, water with an SST below 8 °C was observed only in the northwestern part of the sea and along the western shallows of the basin. As a result, convection did not penetrate the warm layer overlying the CIL, as in 2008 (Fig. 6, *b*).

During the last ten days of January 2012, a cold-water patch appeared in the northern part of the eastern gyre, but convection there reached a depth of only 40 m, even though SST dropped to 7.2–7.3 °C. By the end of January, water with an SST below 8 °C had spread eastwards across the centre of the sea, from the western coast to 38°E.

In February, the cold surface-water area and the convection zone continued to move eastwards. By 10 February, warm water remained only in a strip along the entire Caucasian coast, and this strip persisted until 17 February. Convection was shallow in the centre of the sea, where the lower boundary of the upper quasi-homogeneous layer (UQL) reached a depth of 40–50 m, whereas in the northeastern and southeastern parts of the basin, as well as off the Anatolian coast, cold water extended to depths of more than 100 m. The highest cold content density in mid-February was observed along the Anatolian coast and off the Crimean coast, where cold water flowed in from the northwestern shelf.

By 23 February 2012, almost the entire surface of the deep part of the sea was covered by water with an SST below 8 °C, and convection occurred throughout the sea. Surface water with an SST below 8 °C covered the entire deep part of the sea until 22 March, when a warm patch formed along the RC jet extending from Varna to the Bosphorus outlet. Despite the prolonged cooling, the UQL depth in the centre of the sea did not exceed 50 m. At the same time, due to the transport of cold water to the Anatolian coast by the jet along the western coast and the winter deepening of the pycnocline near the coast, cold water with temperatures below 8 °C extended to depths of about 100 m in this area. During the last ten days of March, despite the presence of cold water at the sea surface, separation of the CIL began because its core temperature fell to almost 6 °C.

Separation of the CIL from the surface continued in April, and by mid-month, the CIL occupied the entire deep part of the sea. At the same time, the CIL in the open sea was relatively shallow, while near the coasts and in coastal anticyclones, it extended to depths of 100 m. This spatial distribution of cold content persisted throughout April (Fig. 10, *a*).

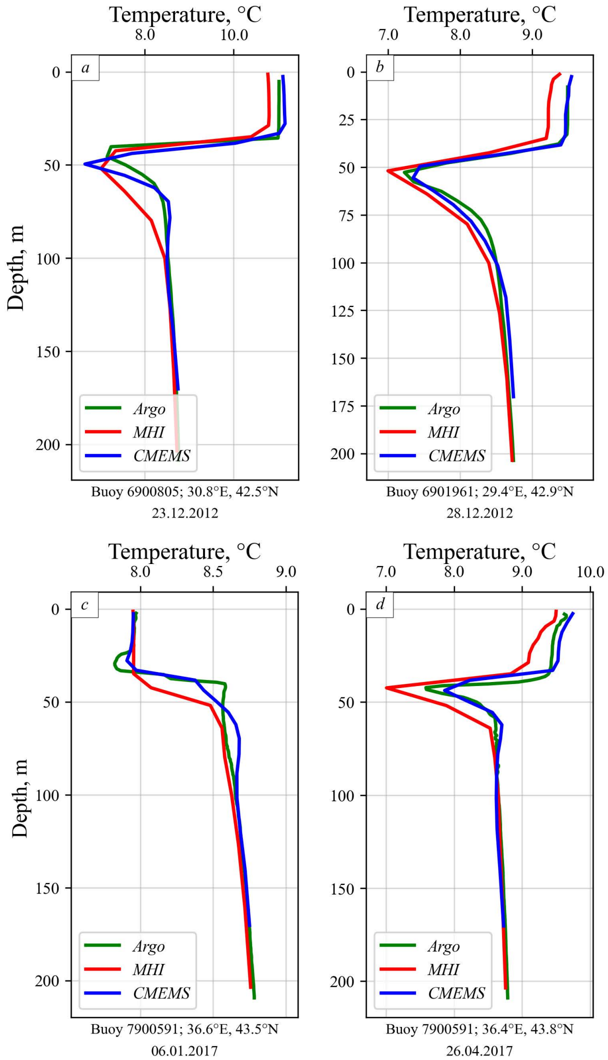


F i g. 10. CIL cold content based on MHI reanalysis data for 2012, 2013, and 2016. Float positions are shown by dots (see Fig. 5 for an explanation)

In May, the continuity of the CIL in the open sea was maintained, and its core deepened slightly, apparently due to the seasonal deepening of the pycnocline in the open sea. In June, intense water exchange between the open sea and the coastal zone occurred (similar to that shown in Fig. 5, *a*), leading to spatial homogenisation of the CIL depths and thickness. The CIL lower boundary in the open sea in June reached a depth of 60–65 m, with the core located at around 50 m.

In July–November, the differences between the CIL characteristics near the coast and in the open sea were reduced by mixing, but complete homogenisation was not achieved. The CIL cold content, which had increased significantly by the end of April, decreased slightly in November–December and was approximately equal to the level observed in 2006.

In December 2012, by the end of the month, water with an SST below 8 °C occupied only part of the northwestern shelf and a narrow strip along the western coast, extending approximately as far as the Bulgaria–Turkey border. Despite the relatively high SST, the CIL still occupied the entire deep part of the sea. At the same time, due to the deepening of the UQL, the CIL became thinner because convection incorporated its upper part into the UQL (Fig. 11, *a*, *b*). As a result, the layer of water with temperatures below 8 °C decreased in thickness, and its core deepened.



F i g. 11. Temperature profiles based on reanalysis and Argo float data for 2012 and 2017

Warm weather continued in January 2013. By the end of the month, cold water at the sea surface had extended along the coast almost to Sinop. In the open sea, patches of water with an SST below 8 °C appeared only intermittently. Nevertheless, a thin CIL occupied the entire deep part of the sea throughout the month. At the same time, along the Anatolian coast, the CIL was relatively thick, with a deepened core, but its cold content had noticeably decreased compared with spring 2012 due to mixing between coastal and open-sea waters. CIL water located off the Anatolian coast was transported by the RC along the Caucasian coast. The persistence of the CIL in the northeastern part of the sea was maintained by the inflow of cold water through the Kerch Strait. The CIL, with its deepened core, was apparently advected by the RC along the Caucasian coast and was also observed in the northeastern part of the sea owing to the inflow of cold water through the Kerch Strait.

By mid-February 2013, the cold surface-water area had extended eastwards to about 31°E. In the northern part of the eastern gyre, patches of cold water formed briefly south of the Kerch Strait outlet. During the last ten days of February, a “tongue” of warm water formed in the west along the RC jet. In the southern part of the western gyre, in the centre of the sea, and in the northern part of the eastern gyre, patches of water with an SST below 8 °C continued to appear intermittently. As a result, the zone of continuous convection, with surface water temperatures below 8 °C, was concentrated to the area west of 32°E, but the UQL did not deepen to the CIL core.

At the beginning of March 2013, water with an SST below 8 °C was still present at the periphery of the western gyre, but by 13 March, the cold-water “tongue” had shifted back towards the western coast along the continental slope. During the last ten days of March, it briefly extended eastwards into the centre of the sea, reaching 37–38°E. However, the short-lived cold spell did not lead to the renewal of the CIL in the eastern gyre. Shallow convection in the area covered by water with an SST below 8 °C also did not renew the CIL within the western gyre. As a result, once the CIL had fully formed by early April, its cold content was at the same level as at the end of 2012. Nevertheless, the CIL occupied the entire deep part of the basin in March, April, and even May. In June, slight CIL erosion began off the Caucasian coast, but elsewhere the layer remained continuous throughout the deep part of the basin in June, July, and August. The CIL cold content decreased steadily during this time due to warming.

In September–October, CIL erosion intensified, and by November, the layer had disappeared over a significant area (Fig. 10, *b*). A further reduction in the CIL area, accompanied by a decrease in cold content, occurred in December, and was favoured by warm weather during that month.

January 2014 was also warm until about 25 January. Water with an SST below 8 °C was present only on the northwestern shelf, and by the end of the month, it had extended along the western shallows as far as Burgas. By early February 2014, the cold-water area along the western coast had expanded, and a “tongue” of cold water had formed around Crimea. In February, cold surface water occasionally extended eastwards as far as 32°E. At certain times, cold-water patches appeared, but due to their short duration, convection was limited. Under these conditions, the CIL area and its cold content continued to decrease due to the warming of its core both in the centre of the sea and near the coast. At the end of February, further cooling of surface waters along the western coast and their advection along the Anatolian coast as far as Sinop led to a slight increase in the integral CIL cold content.

March 2014 was warm, and water with an SST below 8 °C persisted only along the western coast of the sea and the Anatolian coast. The CIL area and its cold content continued to decrease in March. The same trend was observed in subsequent months. In April–May 2014, the CIL still existed as a single continuous area in the centre of the sea, but in June, it became fragmented. By the end of July, only a CIL lens remained at the northern periphery of the eastern gyre, and this lens disappeared in early September. Thereafter, until January 2015, the CIL was absent from the reanalysis maps, and the integral cold content was zero. Note that from April onwards, water with temperatures below 8 °C was no longer recorded by the floats until January 2015. Nevertheless, the CIL did not disappear completely as a structural feature; rather, its core temperature rose above 8 °C.

In December 2014 and the first half of January, the weather was warm, and the cold-water "tongue" along the western coast did not reach Burgas. From mid-January, intermittent patches of water with an SST below 8 °C began to appear in the centre of the sea. As a result, a shallow CIL, separated from the sea surface, began to form locally in the deep part of the sea. These conditions persisted until about 10 February.

During the last 20 days of February 2015, the convection zone associated with SSTs below 8 °C covered the western gyre and the central part of the sea. In March, cold water periodically spread in a broad band along the Anatolian coast and was subsequently replaced by warmer water. As a result, by the end of March, a shallow CIL had formed, with its core at a depth of 30–40 m. The area and cold content of this layer began to decrease, and in April, only isolated CIL patches remained, persisting until the end of June, when the last patch dissipated. Such a rapid disappearance of the CIL is explained by its shallow position and limited thickness. Nevertheless, a CIL-like structure with a core temperature above 8 °C was observed in December 2015.

December 2015 was unusually warm. As a result, water with an SST below 8 °C appeared only over a limited area on the northwestern shelf of the sea. In January 2016, cold water extended only along the western coast of the sea as far as the Bosphorus outlet. Then water with temperatures below 8 °C appeared as patches in the centre of the eastern gyre, at the eastern periphery of the western gyre, and off the Bulgarian coast. In these areas, convection began, and the area of convection expanded by the end of January (Fig. 10, *c*). Despite the low SST, the lower boundary of the UQL was at a depth of about 50 m. When SST dropped in early February, the lower boundary of the UQL deepened only slightly. By about 10 February, cold water at the sea surface had spread eastwards to 31°E in the west and extended in the form of a "tongue" as far as 37° E in the centre of the sea, so that convection also developed in the eastern part of the sea. However, convection reached a depth of only 50 m.

By mid-February 2016, the cold surface-water area had retreated to the western shallows, and by the end of the month, the CIL in the eastern part of the sea had already begun to separate from the surface. By the end of February, the area occupied by the CIL and its cold content had significantly decreased (Fig. 2).

By late February–early March 2016, the CIL had separated from the surface, because, from 5 March onwards, surface water had an SST above 8 °C throughout this area, except for a strip along the western coast. Thereafter, the CIL area shifted eastwards and shrank further, with the CIL becoming thinner and moving closer to the surface. The further reduction in the CIL area in April was accompanied by fragmentation. By the end of May 2016, only one CIL patch remained, roughly in the centre of the eastern gyre, and it disappeared at the end of August.

The last, fourth stage, began with the eastward advance of cold surface water during the first ten days of January 2017. Thereafter, however, only patches of cold water remained at the sea surface in the eastern and western gyres, together with a "tongue" of cold water along the Anatolian coast extending as far as 30° E.

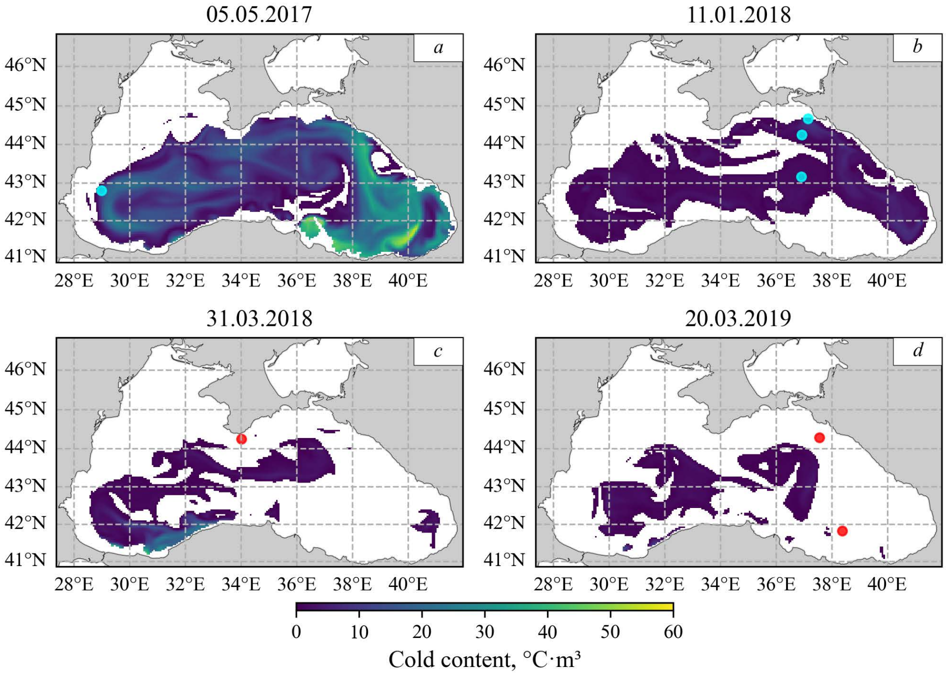
Accordingly, the area of convection associated with SSTs below 8 °C expanded. Temperature inversions developed in the profiles (Fig. 11, *c*). Owing to weather variability, a temperature minimum was observed at a depth of about 30 m in the measured temperature profile. However, as shown in this figure, convective mixing remained shallow.

By the end of January, warm water remained only in a strip along the coast, starting from approximately Trabzon along the Caucasus and Crimean coasts to the northwestern shelf break. At the same time, convection developed actively in both the western and eastern parts of the basin. The current flowing along the western coast of the sea contributed to the formation of a large volume of cold water off the Anatolian coast in the layer extending from the surface to depths of 80–100 m.

By about 25 January, the convection zone covered the entire western gyre and extended eastwards to 38°E. Sea surface temperatures in the eastern part of the basin were relatively low, at 6.5–7.5 °C, but the lower boundary of the UQL in February was at a depth of about 50 m in both the western and eastern parts of the basin.

As noted above, a significant volume of cold water was concentrated off the Anatolian coast. The previously noted "tongue" of warm water extending from Trabzon to the northwestern shelf began to break up in mid-February but did not disappear completely, alternately strengthening and weakening. In early March, it extended along the RC to the Anatolian coast, thereby separating the CIL from the surface; the CIL core was located at depths of 50–60 m. Expansion of the warm-water area off the eastern coast also led to the separation of the CIL from the surface in the southeastern corner of the sea. By the end of March, warm surface water covered the entire deep part of the basin. At the same time, the CIL was completely separated from the surface, but its core in the central part of the sea was located at depths shallower than 50 m. By this time, a thick CIL with a large volume of cold water still remained off the Anatolian coast. In addition, a deep CIL with a high cold content was observed near the Kerch Strait outlet, associated with the inflow of cold water from the Sea of Azov. However, despite the CIL extending throughout almost the entire sea, the integral cold content accumulated by the end of March was noticeably lower than in 2012 and decreased further by the end of April due to a reduction in the layer thickness (Fig. 11, *d*). Moreover, from mid-April, CIL erosion began locally off the Anatolian and Caucasian coasts and over the continental slope of the northwestern shelf. In May, CIL erosion continued (Fig. 12, *a*). The map shows that the CIL with the highest cold content was concentrated in the eastern part of the sea along the Anatolian coast, in the region of the Batumi Anticyclone, and along the Caucasian coast.

In May–September 2017, the CIL spatial distribution remained almost unchanged. It still occupied almost the entire deep part of the sea, although local erosion occurring. As a result of current-driven water transport, the spatial distribution of cold content became more homogeneous, but its overall magnitude decreased slightly from mid-September onwards. By the end of October, CIL erosion had intensified off the Anatolian and Crimean coasts. The integral cold content gradually decreased due to a reduction in CIL thickness, an increase in core temperature, and intensified erosion at its boundaries. Another cause of the reduction in cold content was warming of the CIL from below as the water temperature increased beneath its lower boundary. Warming beneath the CIL was reported in [10], but this process requires further investigation. As a result, by the end of December, the cold content had decreased to the level observed at the end of 2013.



F i g. 12. CIL cold content based on MHI reanalysis data for 2017, 2018, and 2019. Float positions are shown by dots (see Fig. 5 for an explanation)

January 2018 was warm. Water with an SST below 8 °C was present only along the western and southern coasts and extended beyond the Bosphorus outlet. The integral cold content continued to decrease in January, largely due to the ongoing process of horizontal mixing (Fig. 12, *b*). Along with continued heat input from the water above and below the CIL, this process led to a significant reduction in its vertical extent and a further increase in its core temperature.

Warm weather persisted in February, so the cold surface-water area began to move slowly eastwards only from mid-February, retreating about 120 km from the western coast. As a result, the CIL area had noticeably decreased by about 10 February. Only by about 25 February did water with an SST below 8 °C spread as a “tongue” in the centre of the sea, almost reaching the longitude of the Kerch Strait outlet. At that point, convection began to develop, and by early March, it extended across the entire western gyre and the northern part of the sea eastwards to longitude 36.5°E. However, convection reached a depth of only about 40 m.

By mid-March, following a period of warming, the area of water with an SST below 8 °C had retreated to the western shallows, and the CIL had begun to separate from the sea surface in the open sea. Following slight cooling at around 20 March, the cold surface-water area extended slightly away from the western coast, and a cold-water patch appeared in the centre of the western gyre. However, by the end of March, the boundary of the water with an SST below 8 °C had returned to the coast, and the CIL separated from the surface over most of the sea. In March 2018, the formation of a deep CIL through the transport of cold water along the western coast towards the Anatolian coast and then along the RC was clearly evident.

Due to relatively high SST values in the winter of 2018, by the end of March, the CIL occupied only a limited area (Fig. 12, *c*). The integral cold content remained at its early-2018 level. In April, the CIL area and integral cold content changed little. However, in the open sea, the cold content was low due to the increase in the CIL core temperature, while the cold-water layer with the highest cold content persisted along the Anatolian coast.

The strip of deep CIL along the Anatolian coast moved away from the coast in May, apparently due to the transition from the winter to the summer circulation regime [17]. Subsequently, the deep CIL began to mix with the surrounding water, causing the cold content to decrease sharply. By the end of June, only isolated CIL patches with core temperatures below 8 °C remained; they had almost disappeared by mid-August. From about 10 August until the end of the year, temperatures below 8 °C were recorded by only one float operating near the Anatolian coast.

The beginning of January 2019 was warm. Only during the middle ten days of the month did water with an SST below 8 °C appear in a narrow strip in the western gyre and in the centre of the sea. By the end of the month, the area of surface water with an SST below 8 °C began to shrink rapidly, and this contraction continued in early February. Owing to weather variability, the core temperature of the CIL after its separation from the surface was only slightly below 8 °C. In the northern part of the basin, where convection was more prolonged, the CIL core temperature dropped to 7.7 °C.

During the middle ten days of February, cooling occurred, and the area of surface water with an SST below 8 °C expanded in the west and centre of the sea. However, according to the reanalysis data, convection reached a depth of only 30 m despite the low SST. In the southwestern corner, a second period of convection caused the UQL to deepen to 50 m. By mid-March, the sea surface had warmed, and by 20 March, the CIL had formed over a very limited area (Fig. 12, *d*). In April–May, the CIL patches (with core temperatures below 8 °C) became elongated under the influence of currents, and their area and integral cold content decreased rapidly. In early June, the classical CIL disappeared completely. However, a subsurface layer with a pronounced temperature minimum still persisted in some areas in 2019, as confirmed by float observations, but profiles exhibiting a very broad temperature minimum without a distinct core became more common.

Surface water with an SST below 8 °C did not appear in <u>2020</u> until mid-February. According to the vertical temperature profiles derived from reanalysis data, a convection zone could be identified in the northern part of the eastern gyre. However, after 20 March, water temperatures below 8 °C were no longer recorded either at the surface or at depth.

In 2021, water with an SST below 8 °C appeared intermittently in mid-February and mid-March. However, due to the short duration of the cooling episodes, the CIL did not form. Moreover, by 2021, even the subsurface layer with a pronounced temperature minimum had almost disappeared.

Conclusion

The results of this work, as well as those of previous studies based on numerical modeling of the Black Sea circulation, convincingly show that the main mechanism responsible for the annual renewal of the CIL in the basin is winter convection, which penetrates from the surface at least to the core of the layer. The typical CIL thickness observed over long periods was maintained by winter convection throughout the basin. As a result, the CIL cold content and core temperature varied from year to year depending on the intensity of winter surface cooling. The results presented above reveal that during 2000–2005, the CIL was qualitatively and quantitatively close to its mean climatological state, since winter convection in those years developed throughout the basin.

However, significant winter warming in the region in subsequent years led to a substantial reduction in the area and duration of winter convection, thereby weakening CIL renewal. In some cold winters, the CIL was substantially renewed, but as winter convection weakened in subsequent years, the layer degraded relatively rapidly.

The reanalysis data also revealed that the second most important mechanism for CIL renewal is the transport of cold water from the northwestern shelf along the western shallows towards the Bosphorus and then along the Anatolian coast, sometimes as far as the Caucasian coast, leading to the formation of a deep CIL, including within anticyclones. In this case, intense horizontal mixing, which transports cold coastal water to the centre of the basin, also plays an important role. This CIL renewal mechanism is effective only in some years, but, as noted above, it prolonged the persistence of the classical CIL.

Traditionally, the subduction of cold water from the shelf areas of the Black Sea has been considered an important mechanism for CIL renewal. According to the reanalysis data, this is indeed a persistent mechanism, operating not only over the continental slope of the northwestern shelf. Over the shelves, the probability of the episodic formation of a CIL with a core temperature below 8 °C is high even in recent years, when the layer has already disappeared in the open sea. However, even the contribution of subduction from the northwestern shelf to CIL renewal is insignificant at the basin scale. The episodic inflow of cold water through the Kerch Strait is noteworthy, but it is also insignificant for maintaining the CIL.

The reanalysis data also show that one cause of the accelerated CIL degradation over the last decade is the warming of the main pycnocline water at the lower boundary of the layer, which contributes to a reduction in its vertical extent and its upward displacement. Quantitative estimates of the impact of this process require further analysis.

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Anton L. Kholod – calculation, mapping of cold content and its time series, mapping of satellite-derived sea surface temperature, vertical profiles of ARGO floats, analysis of the results, preparation of the manuscript

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