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Original paper

Thermohaline Structure of Western Crimea Shelf Waters

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Abstract
The paper uses oceanographic observations and climatic values at the grid $10' \times 15'$ for 1950–2023 to investigate spatial distribution and seasonal course of the thermohaline structure of Western Crimea shelf waters. In the cold season, the regional spatial thermal structure had a pronounced zonal distribution with cold northern and warm southern parts. During the spring–summer period, the relative location of warm/cold zones changed to the meridional one. The regional haline structure was characterized by a saltier tongue spreading from the open sea and separating brackish waters of the north-western shelf and coastal waters. Over the greater part of the year, the coastal zone was colder and less saline than the outer shelf part. The opposite distribution, when the coastal zone was warmer than the outer shelf part, was observed in the surface layer in April–May and below the seasonal thermocline in the summer–autumn period. Due to frequent upwelling events in summer, salinity in the subsurface layers of the coastal zone from May to September becomes higher than in the outer shelf part. In general, in terms of the thermohaline water structure, the Western Crimea shelf is an intermediate zone between the north-western shelf and the deep part of the Black Sea, the water exchange with which depends of the intensity of the Rim Current and the Sevastopol anticyclonic eddy. Regional water masses or sub-types of main Black Sea water masses were not identified in the study area.

Keywords: thermohaline structure, sea temperature, salinity, climate, shelf, coastal zone, Western Crimea

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Термохалинная структура вод шельфа Западного Крыма

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Аннотация

На основе рассчитанного по данным наблюдений климатического массива температуры и солености на сетке 10′ × 15′ для 1950–2023 гг. рассмотрены пространственное распределение и сезонная изменчивость термохалинной структуры вод шельфа Западного Крыма. Пространственная термическая структура района в холодный период года имеет явно выраженное зональное распределение с холодной северной и теплой южной частями. В весенне-летний период относительное расположение теплых/холодных областей изменяется на меридиональное. Для халинной структуры вод района характерно наличие клина соленых вод открытого моря, разделяющего распресненные воды прибрежной зоны и северо-западного шельфа. Прибрежная зона на протяжении большей части года является более холодной и распресненной, чем мористая часть шельфа. Обратное распределение, когда прибрежная зона теплее мористой части шельфа, наблюдается в поверхностном слое в апреле – мае, а также в слое глубже сезонного термоклина в летне-осенний период. Частые апвеллинги в летний сезон способствуют тому, что соленость в подповерхностных слоях прибрежной зоны с мая по сентябрь становится выше, чем в мористой части шельфа. В целом по характеристикам термохалинной структуры вод шельф Западного Крыма является промежуточной зоной между северо-западным шельфом и глубоководной частью Черного моря, водообмен с которой зависит от интенсивности Основного Черноморского течения и Севастопольского антициклона. Региональные водные массы или подтипы основных черноморских водных масс в исследуемом районе не выделены.

Ключевые слова: термохалинная структура, температура воды, соленость, климат, шельф, прибрежная зона, Западный Крым

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Introduction

The sea area adjacent to the city of Sevastopol and the western districts of the Republic of Crimea constitutes a natural component of the region, playing an important role in its economic development. Regional reference books highlighting climatic conditions and the current state of the environment, including the thermohaline structure of the waters, are needed to solve applied problems.

General features of the hydrology of the area adjacent to the western coast of Crimea are presented in varying degrees of detail in generalized works describing all shelf areas or the Black Sea as a whole [1–4] as well as in works [1), 2)].

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1) Vinogradov, K.A., Rozengurt, M.Sh. and Tolmazin, D.M., 1966. [*Atlas of Hydrological Characteristics of the North-Western Black Sea (for Fishery Purposes)*]. Kiev: Naukova Dumka, 94 p. (in Russian).

In the above studies, the Western Crimea shelf was not distinguished as a discrete region; rather, it was considered part of the extensive north-western shelf. Its proximity to the deep-water segment of the Black Sea is noteworthy with respect to the similarity of conditions.

The characteristics of various oceanographic phenomena and processes specific to the area have been addressed in works [3), 4)] [6–12]. Much research is devoted to the circulation of waters of the north-western shelf in general and the Sevastopol anticyclonic eddy in particular (e. g., works [2), 5)] as well as [2–4, 13–21]). The advection of waters affects the thermohaline structure significantly, especially at the boundaries of areas with different hydrological structure of waters.

The regional description of the seasonal variability of the thermohaline structure of waters related to this area was published more than 20 years ago on the basis of archival data available at that time and was limited to the Sevastopol seaside [12].

The aim of the work is to describe the seasonal variability of the thermohaline structure of Western Crimea shelf waters based on the observation data for 1950–2023 with an assessment of the main differences between the open and coastal parts of the study area.

Materials and methods of study

The shelf area adjacent to the western coast of Crimea is one of the areas of the Black Sea with a fairly high availability of oceanographic data. In total, the data bank of Marine Hydrophysical Institute of RAS includes 37,046 oceanographic stations (1460 sets/cruises) made in the study area (44° 20′–45° 30′ N, 32°–33° 35′ E) in 1910–2023 [6)] (Fig. 1). The 1950–2023 period covering two World Climate Organization climate periods was chosen for the calculation of climate values (10,673 stations) (Fig. 2).

Climatic estimates of temperature and salinity were calculated based on decade profiles from the thermohaline field reanalysis array, which are interpolated values of primary measurements at the regular grid 10′ × 15′ using the methodology described in [22]. The relative degree of coverage of the study area with interpolated values reached 90% in 1960–1980, 20% in 1995–2015 and 40% after 2016. For 1950–2023, monthly temperature and salinity values at grid nodes were calculated and taken as climatic normals.

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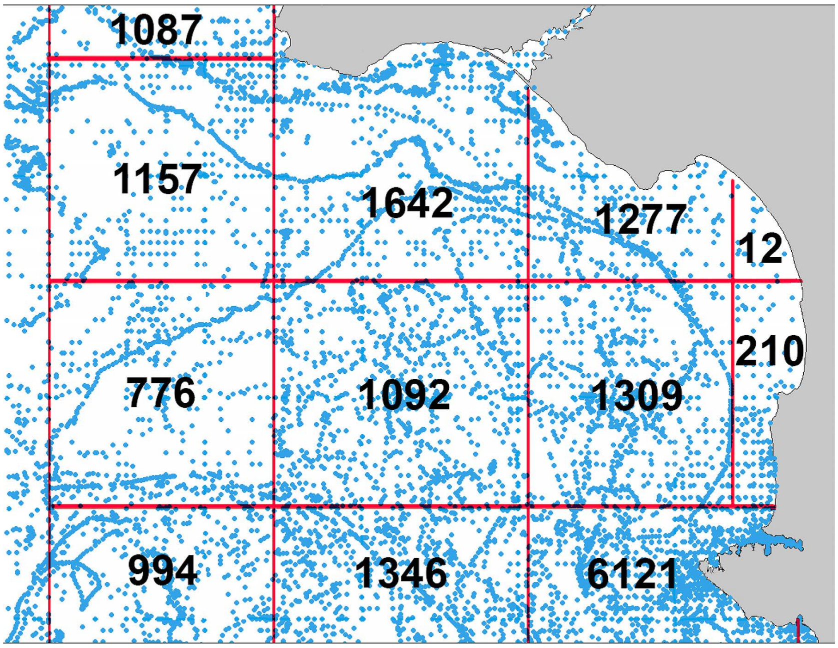
2) Nelepo, B.A., ed., 1984. [*Variability of Hydrophysical Fields of the Black Sea*]. Leningrad: Gidrometeoizdat, 240 p. (in Russian).

3) Ilyin, Yu.P. and Grishin, G.A., 1988. [The Summer Spreading of the North-Western Black Sea and the Possibility of its Control by Satellite Video Data]. In: Vasiliev, L.N., 1988. [*Geographic Interpretation of Aerospace Data*]. Moscow: Nauka, pp. 119–125 (in Russian).

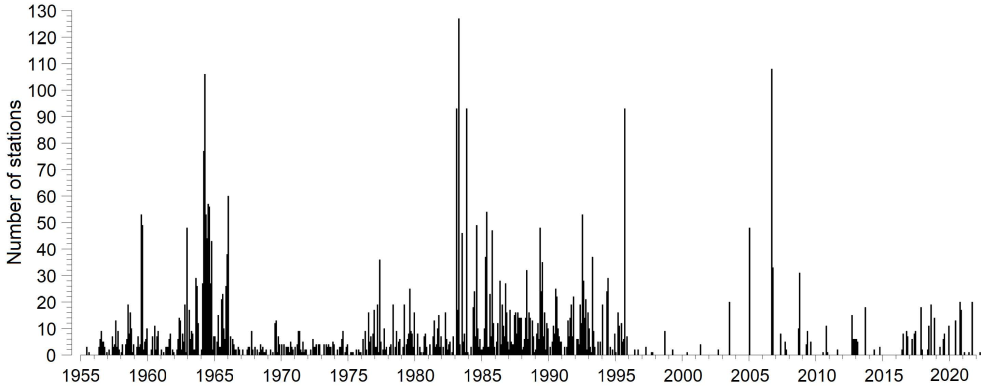
4) Tuzhilkin, V.S., 2008. [*Seasonal and Multiyear Variability of the Thermohaline Structure of the Black Sea and Caspian Sea Waters and the Processes of its Formation. Extended Abstract of DSc Thesis. Geographical Sciences*]. Moscow, 46 p. (in Russian).

5) Bolshakov, V.S., 1970. [*Transformation of River Waters in the Black Sea*]. Kiev: Naukova Dumka, 328 p. (in Russian).

6) Godin, E.A., Belokopytov, V.N., Ingerov, A.V., Plastun, T.V., Galkovskaya, L.K., Kasianenko, T.E., Zhuk, E.V. and Isaeva, E.A., 2019. *The Black Sea: Hydrology. 2018* [Database]. Moscow. State Registration No. 2019621008 (in Russian).



F i g . 1. Location of oceanographic casts in the shelf area near the Western Crimea coast in 1910–2023 and number of stations in 20′ × 30′ squares



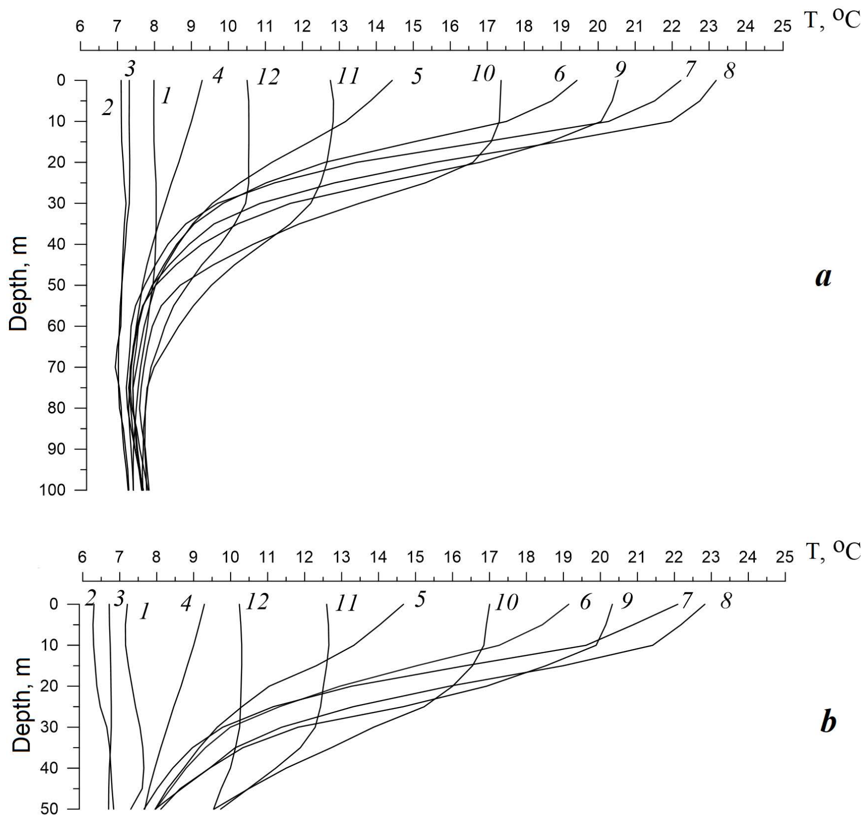
F i g . 2 . Time-series of monthly number of oceanographic stations in the study area

Results and discussion

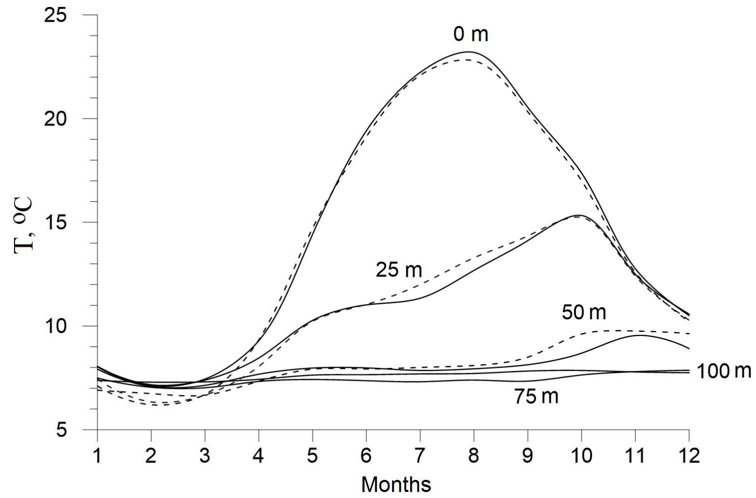
Water temperature

The seasonal course of the vertical thermal structure of the waters in the study area is generally characteristic of the Black Sea. From January to March, the water temperature remains consistent throughout the layer. From May to August, a sharp thermocline develops, and the frequency of occurrence of the upper mixed layer during this period of the year is minimal. A phase delay of the seasonal cycle is observed with depth (Figs. 3, 4).

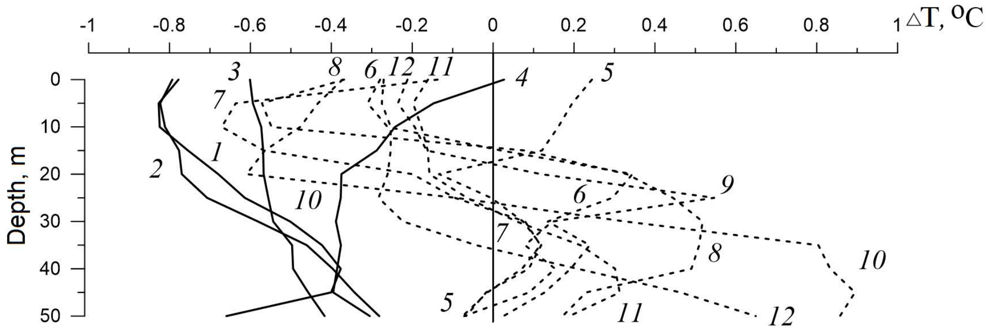
To separate the open and coastal segments of the shelf, an isobath of 50 m was adopted. From January to April, the coastal zone in the entire layer is colder than the rest of the shelf; the difference in temperature between the waters of the coastal zone and the outer shelf part reaches 0.8°C and does not change sign with depth



F i g . 3 . Climatic monthly vertical temperature profiles in the South-Western Crimea shelf area: in the outer shelf part (*a*), in the coastal zone (*b*). Digits stand for month numbers



F i g . 4 . Climatic seasonal course of water temperature in the Western Crimea shelf area at different depths. Dashed lines denote temperature values in the coastal zone (depth < 50 m), solid lines are those in the outer shelf



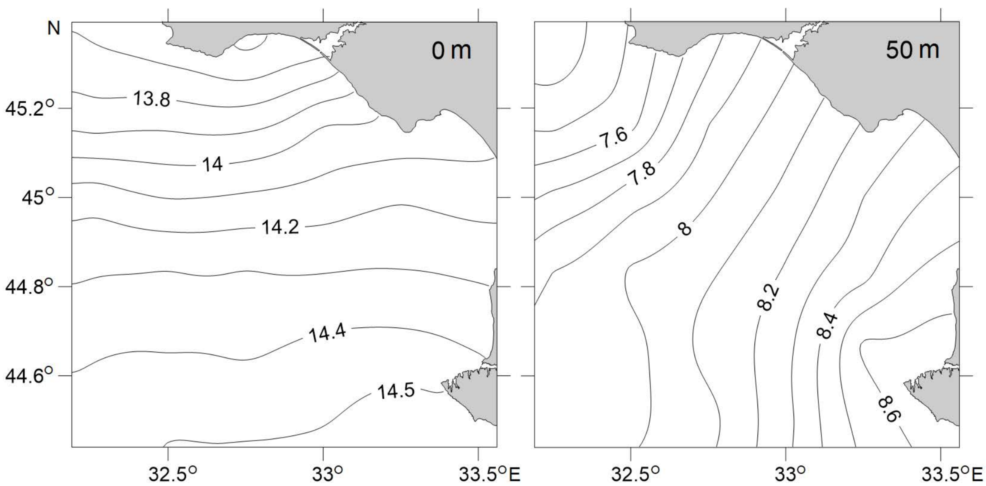
F i g . 5 . Differences of climatic monthly temperature between the coastal zone and the Western Crimea outer shelf. Dashed lines denote months when the difference in values changes its sign with depth, solid lines are months without changes. Digits stand for month numbers

(Fig. 5). During the rest of the year, the temperature of coastal waters in the surface layer is generally lower than in the outer shelf part ($\Delta T \leq 0.6$°C) and it is higher in the layer below the thermocline ($\Delta T \leq 0.9$°C) (Fig. 5).

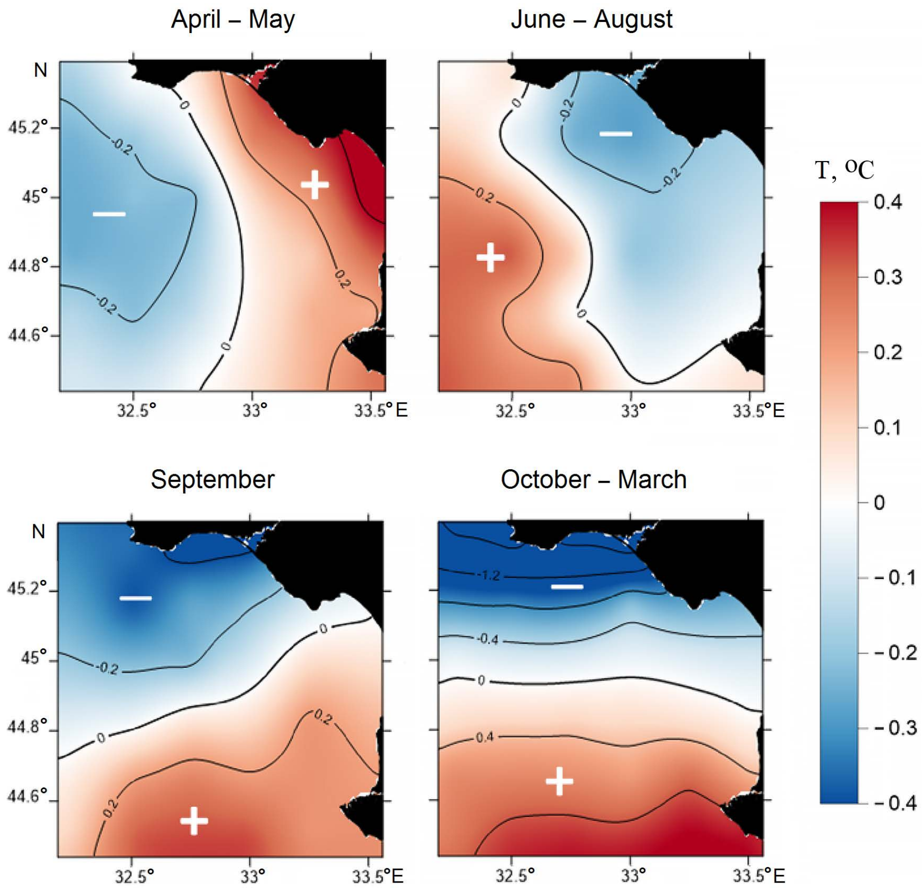
The spatial thermal structure of the area as a whole has a clearly pronounced zonal distribution with cold northern and warm southern parts. With depth, the southern direction of temperature growth changes to the south-eastern direction due to the influence of cold bottom waters of the north-western shelf (Fig. 6).

During the annual cycle, the spatial ratio of warm and cold areas in the temperature field changes (Fig. 7). The greatest deviation from the mean annual distribution in the surface layer is observed in April and May, when the entire coastal zone is on average 0.3–0.4°C warmer than the open part, and in summer, when coastal waters, on the contrary, are 0.2°C colder. This is due to the fact that under the conditions of spring warming and low winds, the coastal zone warms up faster than the open shelf part, and in summer the influence of surges and upwelling events in the coastal zone is most pronounced. From September to March, the thermal field corresponds to the yearly distribution, with the zonal contrast in water temperature being minimal in September.

The geographical position of the Western Crimea shelf between the deep sea and the north-western shelf implies the possibility of advection of cold intermediate layer (CIL) waters from these areas. The results of individual oceanographic measurements showed signs of penetration of the CIL waters into the study area from both northern and southern directions. As for the climatic distribution of water temperature and salinity, it can be concluded that the CIL near the Western

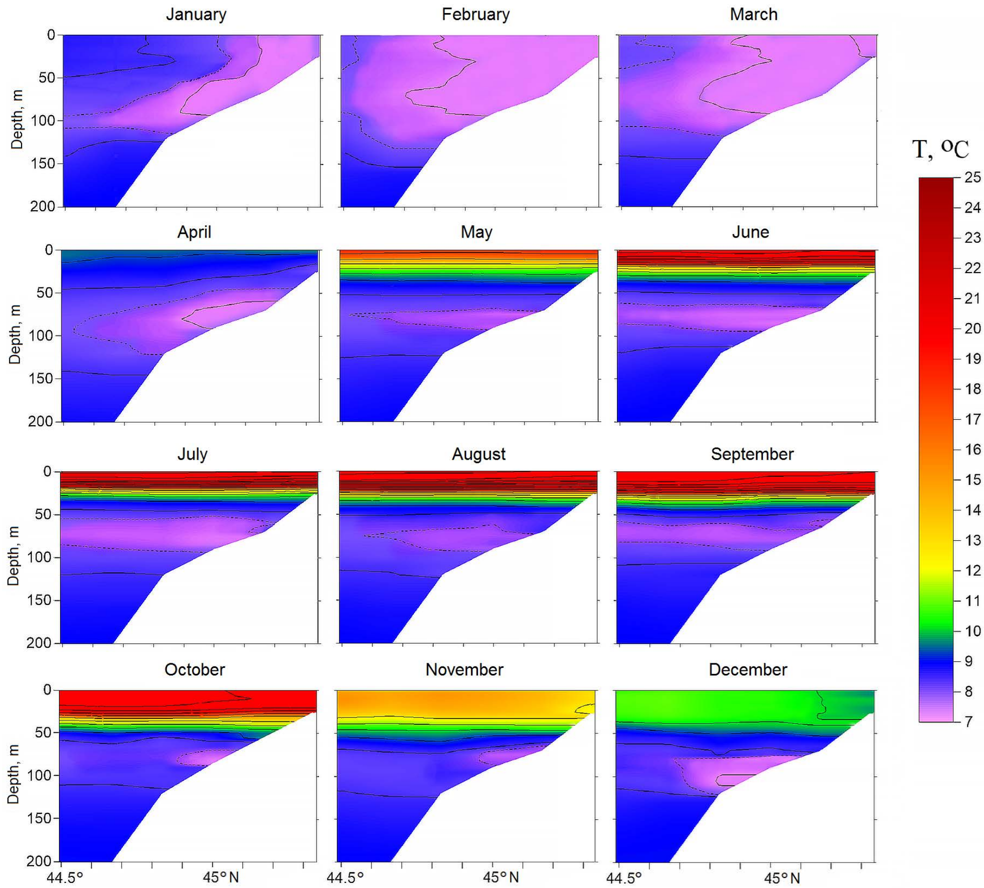


F i g . 6 . Climatic yearly water temperature fields in the Western Crimea shelf, °C, at depths of 0 and 50 m



F i g . 7 . Generalized types of spatial water temperature distribution in the surface layer of the Western Crimea shelf by deviations from the region area averaged value. Key: "+" – positive anomalies, "–" negative anomalies

Crimea coast is formed mainly on the north-western shelf. Previously, high-resolution winter–spring surveys near the continental slope of the north-western shelf showed that advection of bottom waters into the deep sea occurred mainly in the area between 30° and 32° E. The climatic monthly values of water temperature on the central meridional section of the study area along 32° 45′ E (Fig. 8) show clearly that the sliding of cooled waters towards the open sea also occurs near the Crimean coast.

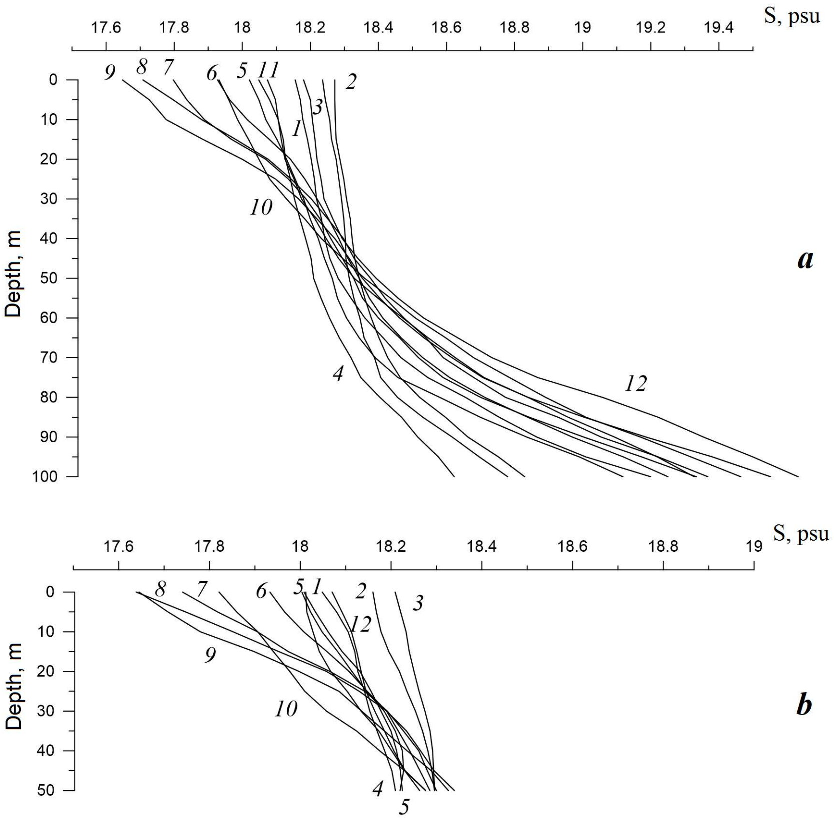


F i g . 8 . Climatic monthly water temperature in the Western Crimea shelf along the 32° 45′ E section

Salinity

The annual course of the vertical structure of salinity in the study area (Fig. 9) is conventionally divided into two seasons. From November to May, weak haline stratification in the 0–70 m layer is almost the same as in the deep Black Sea. In June–October, vertical salinity gradients increase and the stratification of the area is intermediate between the north-western shelf with highly stratified waters and the deep sea.

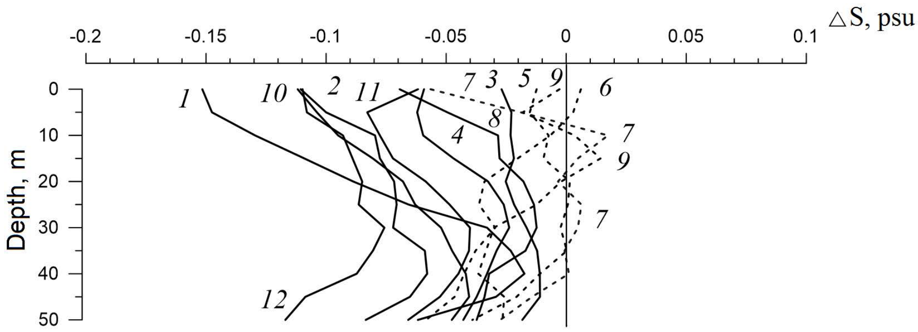
For most of the year, the coastal zone (up to 50 m depth) is more brackish in the entire water column than the rest of the shelf (Fig. 10). From May to September, salinity in the subsurface layer of the coastal part is higher than in the outer part, which is connected with intensification of vertical mixing during upwelling events.



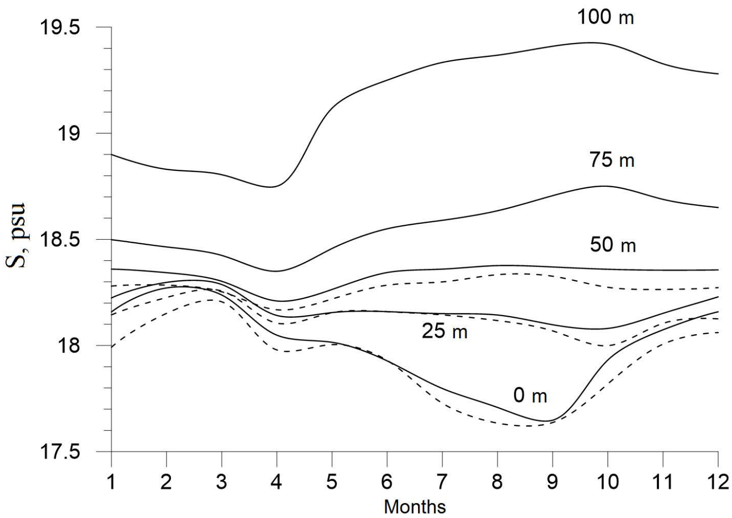
F i g . 9 . Climatic monthly vertical salinity profiles in the Western Crimea shelf area: in the outer shelf part (*a*), in the coastal zone (*b*). Digits stand for calendar month numbers

The seasonal course of salinity at different horizons in the study area and in many other areas of the Black Sea differs significantly (Fig. 11). The salinity minimum in the surface layer of this area is shifted to early autumn, whereas in the rest of the Black Sea, the minimum is observed in spring and summer. On the Western Crimea shelf, in the 50–100 m layer, the salinity minimum is reached in April, with its maximum in October, which is also not typical for the sea as a whole. This is largely determined by the seasonal dynamics of the Sevastopol anticyclonic eddy which affects water exchange of the study area with the Rim Current and the north-western shelf.

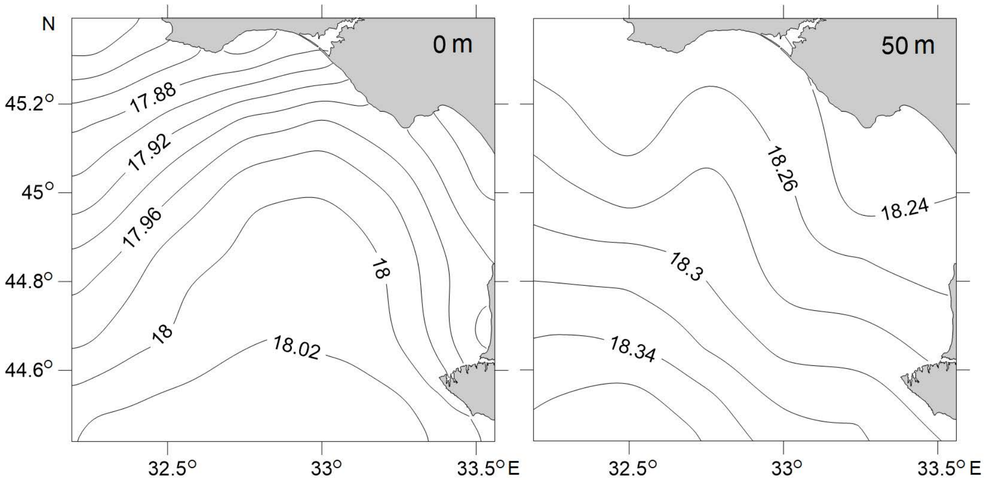
The spatial haline structure of the area waters (Fig. 12) is characterized by the presence of a saltier tongue coming from the open sea and separating the brackish waters of the north-western shelf and the coastal zone. The spatial orientation of the saline water area does not change much with depth.



F i g . 1 0 . Differences between climatic monthly salinity values in the coastal zone and the Western Crimea outer shelf. Dashed lines are salinity diagrams for months when the difference in salinity values changes its sign with depth, solid lines are those for months without changes

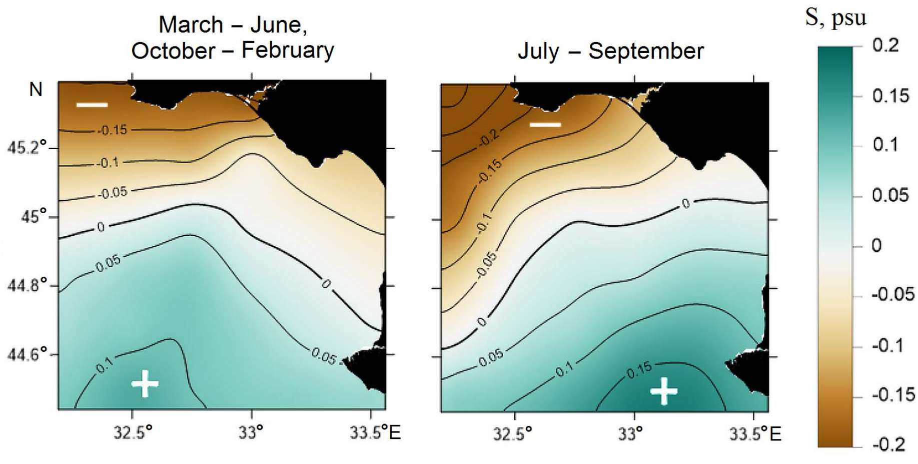


F i g . 1 1 . Climatic seasonal course of salinity in the Western Crimea shelf area at different depths. Dashed lines denote values in the coastal zone (depth < 50 m), solid lines are those in the outer shelf



F i g . 1 2 . Climatic yearly salinity fields, psu, in the Western Crimea shelf at depths of 0 and 50 m

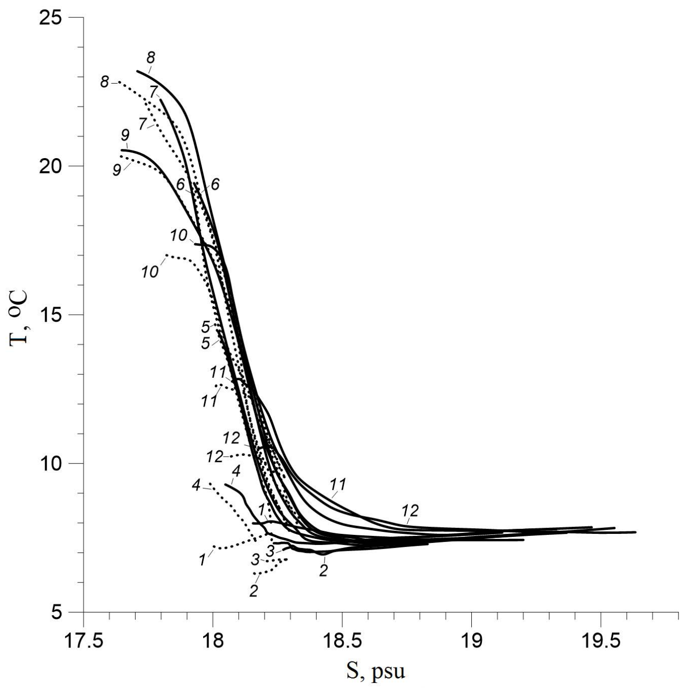
The most significant deviations of salinity from the spatial pattern of yearly distribution (Fig. 13) occur in summer when salinity increases in the surface layer of the coastal zone under low water conditions in small rivers of Crimea, surge and upwelling events.



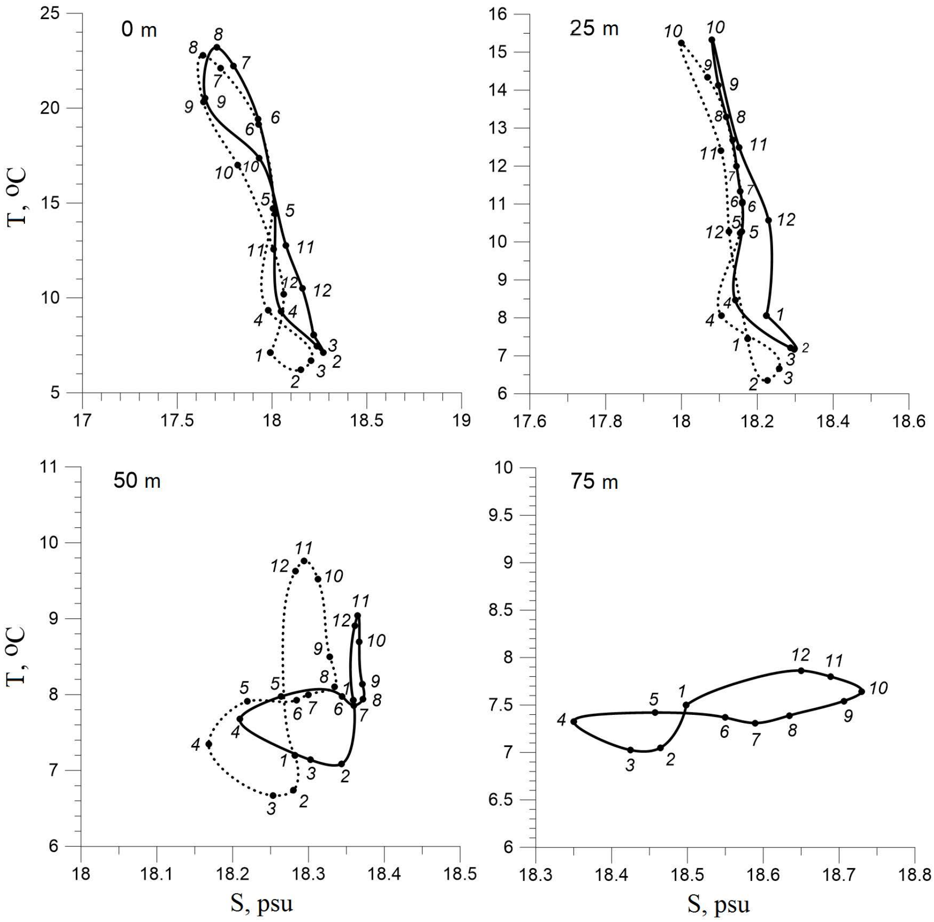
F i g . 1 3 . Generalized types of spatial salinity distribution in the surface layer of the Western Crimea shelf by deviations from the region area averaged value. Key: "+" – positive anomalies, "–" negative anomalies

T,S indices

Monthly T,S curves are qualitatively consistent with the distribution of water masses in most areas of the Black Sea (Fig. 14). Seasonal course of T,S indices (Fig. 15) reflects patterns common to the basin. In the surface layer, during the transition from winter-spring to summer-autumn period, the increase in water temperature is accompanied by a decrease in salinity. In the CIL, seasonal changes are characterized by a joint increase in water temperature and salinity from winter to summer. In the main pycnocline, the seasonal cycle is qualitatively similar to that of the surface layer but with a larger amplitude of salinity fluctuations and a much smaller amplitude of temperature. Characteristic loops on T,S trajectories arising from relative phase shifts between seasonal cycles of temperature and salinity are related to different ratios of contributions of heat, water balance and intensity of vertical mixing of waters.



F i g . 1 4 . Climatic monthly T,S curves in the Western Crimea shelf. Dotted lines denote values in the coastal zone (depth < 50 m), solid lines are those in the outer shelf. Digits stand for calendar month numbers



F i g . 1 5 . Climatic seasonal course of T,S indices in the Western Crimea shelf for various depths. Dotted lines denote values in the coastal zone (depth < 50 m), solid lines are those in the outer shelf. Digits stand for calendar month numbers

Conclusion

On the basis of oceanographic observations for 1950–2023, climatic monthly values of temperature and salinity were calculated at the grid 10′ × 15′ and the seasonal variability of the thermohaline structure of the Western Crimean shelf waters was analysed.

In the cold season, the regional spatial thermal structure of the area has a pronounced zonal distribution with cold northern and warm southern parts. During the spring–summer period, the relative location of warm/cold zones changes to the meridional one. The CIL near the Western Crimea coast is formed in winter on the northwestern shelf. In summer, when the general water circulation weakens, the CIL waters can also penetrate to the study area from the deep sea.

The regional haline structure was characterized by a saltier tongue spreading from the open sea and separating brackish waters of the north-western shelf and coastal waters. In the seasonal course of salinity on the Western Crimea shelf, in contrast to its seasonal course in other areas of the Black Sea, the minimum of salinity in the surface layer was observed in early autumn, which is associated with regional water circulation.

Over the greater part of the year, the coastal zone is colder and less saline than the outer shelf part. The surface layer in the coastal zone under intensive heating and weak winds is warmer than in the outer part of the shelf in April and May and below the seasonal thermocline in the summer–autumn period due to less heat exchange with the CIL. Due to frequent upwelling events in summer, salinity in the subsurface layers of the coastal zone from May to September becomes higher than in the outer shelf part.

In general, in terms of the thermohaline water structure, the Western Crimea shelf is an intermediate zone between the north-western shelf and the deep part of the Black Sea, the water exchange with which depends of the intensity of the Rim Current and the Sevastopol anticyclonic eddy. Regional water masses or sub-types of main Black Sea water masses were not identified in the study area.

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