The ecological condition of coastal waters off the Heracles Peninsula
(Crimea, the Black Sea)

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Abstract
The results of the long-term monitoring of coastal waters off the Heracles Peninsula (Crimea, the Black Sea) are presented. The abiotic and biotic parameters, indicating the ecological condition of the coastal zone, have been studied. The following parameters have been measured by standard methods: water temperature, illuminance, concentration of particulate matter, organic matter, primary production, intensity of biotic reproduction of particulate matter, phytoplankton and meroplankton species diversity, abundance, and biomass, as well as shell morphometrics and sex ratio in mussel *Mytilus galloprovincialis* Lam. It has been found that upwelling water circulation is typical for the coastal waters off the Heracles Peninsula. The mean annual sea surface temperature over the study period 2000-2016 proved to be 2.7°C higher than that in the early 20th century. The maximum values of phytoplankton primary production are associated with inner waters of coves and with increased $T_{\text{water}}$ and $E_{\max}$ values. A reduction in phytoplankton and meroplankton diversity and a dominance of eurybiontic species have been recorded from the waters subject to anthropogenic impacts. The most pronounced shift of sex ratio toward predominance of *M. galloprovincialis* males and a high mussel H/L shell index are observed in waters with increased technogenic load. The taxonomic structure of phytoplankton and meroplankton, sex ratio, and morphometric parameters of bivalves are the sensitive tools of ecological monitoring to assess the condition of the surrounding aquatic environment.

Key words: sea surface temperature, suspended matter, primary production, phytoplankton, meroplankton, *Mytilus galloprovincialis*, Black Sea, Heracles Peninsula.

Introduction

The coastal zones are the most complex and at the same time the most interesting ones for study. There is cooperation of four parts of geographical environment - the hydrosphere, the atmosphere, the lithosphere and the biosphere and about 60% of the world's population lives there (Golubev 1999). Coastal zones are most of all susceptible to anthropogenic impact. The application of an interdisciplinary approach is one of the most promising methods of its ecological state studying.
Heracles peninsula is located in the south-west of Crimea. It is washed by the Black Sea. In the east, the land border runs along the line connecting Sevastopol and Balaklava bays. On the north-west of the peninsula there are rias coasts and about 30 bays. On the coastline there are densely populated urban settlements.

During the long-term environmental monitoring of the Herakleian peninsula coastal waters, a large dataset was obtained. The dataset includes abiotic and biotic parameters characterizing ecological state of the coastal zone. Species variety of flora and fauna is an indicator of ecosystem sustainability. Data of qualitative and quantitative composition of phyto- and meroplankton reflect the ecological state of coastal waters. The mussel *Mytilus galloprovincialis Lam.* is one of the environment-forming species in the Black Sea. Bivalves are often used as contamination bioindicators of the aquatic environment with various toxicants (Kirichuk 2003; Yap 2005).

The change of sex ratio and morphometric characteristics of mussels are a specific response to environmental pollution.

The purpose of this work is to assess the influence of abiotic and biotic components on the ecosystem of Heracleian Peninsula coastal zone.

**Material and Methods**

Coastal zone of the Heracles Peninsula was investigated in the period 2000 – 2016. The material was collected over the depths of 10-15 m. For the study we choose water areas with anthropogenic load: Sevastopol (Station 1), Kruglaya (Station 3) and Balaklava Bays (stations 6, 7, 8). The external raid of Sevastopol (station 2) and Balaklava Bay (stations 4, 5) – unpolluted water areas. Map of the study area is presented (Fig. 1).

![Figure 1. Map of the research area.](image-url)
The measurement of the sea surface temperature (SST) was carried out using a surface thermometer according to the method (Guide to hydrological..., 1977). Measurements of the thermochaline characteristics of seawater were carried out using an autonomous min probe SD204 «SAIV A/S Norway».

To study the primary production (PP, mgC m\(^{-3}\) days\(^{-1}\)) of organic matter (OM), the radiocarbon method was used (Guidance on determining..., 1960). The illumination (I, kLx) was measured near the surface layer with a light meter «Yu-116» with the determination \(I_{\text{max}}\) - maximum daylight illumination. The concentration of suspended matter (\(C_{\text{susp}}, \text{mg} \text{ (dry)} \text{ l}^{-1}\)) in surface water samples by the method of "membrane filtration" was determined (Vityuk, 1983). 1.0-1.5 liters of water was filtered through pre-weighed nucleopore filters with a pore size of 0.45 \(\mu\text{m}\), followed by their drying and weighing on a «Sartorius» microanalytic balance.

The intensity of biotic reproduction of a suspended substance of surface water was represented as the value of the period of transformation of the mass of suspended matter (\(P_{\text{trans}}, \text{day}\)) (Popovichev et al, 2014).

To study phytoplankton, water samples (\(V = 1.5 \text{ L}\)) were taken from the surface, condensed by a reverse filtration method through nuclear membranes (\(D_{\text{por}} = 1 \mu\text{m}\)). The samples was treatment by direct counting of microalgae in a live and concentrated drop (\(V = 0.01 \text{ ml}\)), in a camera (\(V = 1 \text{ ml}\)) using a light microscope «Jenaval». The abundance and biomass of phytoplankton was calculated using the Plankton computer program (Lyakh & Bryantseva, 2001).

Meroplankton was selected by the Jedi net (diameter 36 cm, size 135 \(\mu\text{m}\)). Samples were processed on a living material by total counting of larvae in Bogorov's camera, using binocular MBS-9, and light microscope «Micmed-5».

\(M. \text{ galloprovincialis}\) with a shell size of \(30.20 \pm 0.02\) and \(50.30 \pm 0.04\) mm was collected in the water area on the stations (1, 2, 8) (Fig. 1). Using the caliper with an accuracy of 0.1 mm, the following parameters were measured: L - length, mm; H - height, mm; D - width, mm (Dehta & Katalevsky 2000). To determine the form of the shell used indexes of ratio: the height to its length of shell \(H/L\) (elongation), width to length \(D/L\) (convexity). To determine the sex and maturity stage of gonads was used binocular «MBI-6» (Pirkova 1994).

Results and discussion

During the study period, we analyzed the temporal trends in sea surface temperature (SST) in the coastal zone off the Heracles Peninsula. The following main seasons of year have been determined: winter (January to March), shorter spring (April and May), longer summer (June to September), and autumn (October to December). The SST varied within a range from 3.8 to 29.8\(^{\circ}\text{C}\). According to data provided by Zernov (Zernov 1913), during the first decade of the 20\(^{\text{th}}\) century, the annual mean SST off the Sevastopol coast was 12.9\(^{\circ}\text{C}\). Thus, over the past 100 years, the annual mean SST increased by 2.7\(^{\circ}\text{C}\). Our study showed that the coldest year was 2003 (14.5\(\pm\)0.6 \(^{\circ}\text{C}\)), while 2010 (17.1\(\pm\)0.7 \(^{\circ}\text{C}\)) was extremely warm. The value of the positive linear SST trend for the period 2000–2016 constituted 0.06\(^{\circ}\text{C}/\text{year}\) (Fig. 2).

SST in summer season can change dramatically during a coastal upwelling event. Coastal upwelling is generated by winds blowing along the shoreline. For the northwestern coast, the offshore winds are those blowing from the east; and for the southeastern coast, blowing from the west (Repetin et. al., 2003). In the area of the Bay of Sevastopol, the frequency and intensity of upwelling events is lower than those off the Balaklava coast (Fig. 3). This distribution is explained by the presence of a zone of calmness or weak winds in the coastal area off the Heracles Peninsula under the effect of strong eastern wind flows over the Crimea and the Black Sea. The movement of water masses driven by upwelling influences also plankton organisms: their species composition and abundance change.

The minimum salinity value (13.4 \(\%\)) was recorded in 2004 during heavy precipitation events in the northern part of the Balaclava bay (st. 8). The highest salinity (18.01 \(\%\)) was observed at the station 6 in 2001 during intensification of vertical convection, as the surface water was cooled (Lomakin & Popov 2013). Salinity increased from the apex part of the bays to open waters.
In the period 2009–2016, values of biotic and abiotic parameters in the coastal waters off Sevastopol (st. 2) varied within the following ranges: $PP$ - from 0.8 to 931.3 mgC·m$^{-3}$·days$^{-1}$, $C_{susp}$ - from 0.2 to 3.0 mg (dry) l$^{-1}$, $P_{trans}$ - from 2.7 to 1667 days, $I_{max}$ - from 9.5 to 101.0 kLx. The values of concentrations of inorganic forms of nitrogen and phosphorus, responsible for the mineral nutrition of phytoplankton, varied within the ranges mcg l$^{-1}$: nitrites - from 0.1 to 8.1, nitrates - from 6.6 to 653.0, ammonium - from 1.0 to 424.2 and phosphates - from 1.1 to 105.1. An analysis of the data showed that the maximum values of primary production ($PP$ – 100 mgC·m$^{-3}$·days$^{-1}$) (Fig. 4A), exceeding the relative level of eutrophication, are mainly associated with increased values of $T_{water}$ and $I_{max}$ characteristic of the spring–summer period. They reflect the positive relationship between the physical factors of heat and light (Fig. 4D). The values of $PP$ above 100 mgC·m$^{-3}$·days$^{-1}$ (Phinenko et al. 2009) indicated a hypereutrophication of waters. The $P_{trans}$ values
correlated negatively with the values of \( T_{water} \) (Fig. 4C). The dynamics of variations in the concentration of total suspended matter (TSM) did not show any functional relationship with SST (Fig. 4B).

**Figure 4.** Relationship between surface water parameters and seasonal temperature changes (\( T_{water} \), °C): A - primary production, B - concentration of total suspended matter, C - period of mass of suspension, D - maximum daylight illumination.

In the summer seasons of 2010 and 2016, the SST was abnormally high (up to 29.8°C), which caused blue-green algae (Cyanobacteria, *Lyngbya* sp) to appear in the coastal waters off Sevastopol. At this time, the values of PP and concentration of TSM in the water samples were characterized by 64.1 mgC·m\(^{-3}\) day\(^{-1}\) and 1.6 mg (dry) l\(^{-1}\) (02.08.2010) and 93.2 mgC·m\(^{-3}\) day\(^{-1}\) and 0.8 mg (dry) l\(^{-1}\) (11.08.2016), respectively. In the winter of 2015, the studies were carried out in Balaklava (st. 4, 5, 6, 7) and Kruglaya (st. 3) bays. The inner waters of Balaklava Bay (st. 7, 8) had high PP (mgC·m\(^{-3}\) day\(^{-1}\)) (356.8 – 428.0) and low \( T_{obs} \) (4.9 – 6.7) values, respectively. The concentration of suspended matter in the surface layer was (mg (dry) l\(^{-1}\)) (1.4 – 2.3). In the outer water area of Balaklava Bay (st. 4, 5), low values of PP (mgC·m\(^{-3}\) day\(^{-1}\)) (25.1 – 68.7) were recorded, compared to the inner waters, \( P_{trans} \) (7.3 – 769.2) and \( C_{susp} \) from 0.4 to 16.0 mg (dry) l\(^{-1}\). The high values of \( C_{susp} \) were confined to the site of discharge of city’s sewage waters (st. 6). In Kruglaya bay (st. 3): PP – from 16.8 to 439.1 mgC·m\(^{-3}\) day\(^{-1}\), \( C_{susp} \) – from 1.1 to 4.2 mg (dry) l\(^{-1}\), \( P_{trans} \) – from 8.5 to 82.0 day.

The above estimates of the biotic and abiotic parameters reflect the ecological conditions for the life functions of microbiota in the surface layer of waters off the Heracles Peninsula. The increased values were recorded from waters with limited water exchange and subject to anthropogenic impacts.

The biodiversity of phyto- and meroplankton also reflects the ecological condition of the water area. A total of more than 250 species and intraspecies taxa of plankton microalgae, belonging to 9 orders, were found in the coastal waters of the peninsula. The greatest contribution to the total number of species was made by Bacillariophyta and Dinophyta (79 – 87%). In the winter–spring period, the ratio of these groups was shifted towards diatoms; in the summer and autumn, there was a shift towards dinophytes. The contribution of other algal groups during the year was not larger than 8 – 13% of the total number of species. This taxonomic structure is typical of most coastal waters in the Black Sea. The values of abundance and biomass varied depending on season and study area. The northern part of the peninsula is distinguished by
higher quantitative characteristics of phytoplankton. This is related to the influence of the Bay of Sevastopol waters transferring large amounts of nutrients discharged by the Chernaya River, which causes a mass proliferation of planktonic algae, reaching a level of “bloom” of water (Senicheva, 2014). The water “bloom” events were most frequently caused by Bacillariophyta and Haptophyta. During winter, when intensive convective mixing of water and, consequently, the increase in amount of nutrients occur, diatoms (Skeletonema (to 4 million cells • 1\(^{-1}\)) and Pseudo-nitzschia (to 5 million cells • 1\(^{-1}\)) reached the maximum level of proliferation. Cocolithophorid (Emiliania huxleyi), which caused the “blooms”, appears at a SST above 10°C. Thus, the unusual white-blue color of water, caused by intensive proliferation of E. huxleyi (4 - 6 million cells • 1\(^{-1}\)), was observed from May to June 2012. The diatom Chaetoceros socialis, manifested rapid proliferation in spring, with the maximum abundance in the waters of the Bay of Sevastopol (16 million cells • 1\(^{-1}\)). By the end of the summer, large-sized diatoms dominated the phytoplankton Pseudosolenia calcarius and Proboscia alata. Their biomass reached 14 g • m\(^{-3}\). The blooms of large-celled diatoms were also influenced by the increase in the volume of waters from the Chernorechinsky Reservoir, rich in nitrates and dissolved organic matter, discharged into the bay (Senicheva 2014). In recent years, cases of mass proliferation of large-celled species in coastal waters of the Crimea have become more frequent, and their biomass has increased by an order of magnitude as compared to the values in the 1990s (Senicheva, 2014). The proliferation of P. calcarius and P. alata continued until November; subsequently, they were joined by C. pelagica, the biomass of which reached 30 g • m\(^{-3}\) in November 2014 that was associated with the hydrological processes. All the bays of the study area are characterized by a high degree of anthropogenic load, and the waters of the Balaklava and Kruglaya bays are exposed to contamination with dissolved organic matter (Lomakin & Popov 2013). Therefore, the constant presence and sometimes a high abundance (up to 300 thousand cells • 1\(^{-1}\)) of small-celled green and heterotrophic cryptophytic algae and cyanobacteria, characteristic of waters polluted with dissolved organic matter, was observed during the warm period of year.

Thus, the qualitative and quantitative characteristics of phytoplankton in the waters off the peninsula are determined by the hydrological and hydrochemical specifics of the area, as well as by the anthropogenic component, including the discharge of the Chernaya River regulated with the dam.

Pelagic larvae of benthic invertebrates (meroplankton), when settling, get recruited to benthic populations. Consequently, the structure of meroplankton reflects the state of the fouling and benthic communities. Larvae of invertebrates were found in the plankton: Hydrozoa, Phoronidea, Nemertea, Bryozoa, Polychaeta, Bivalvia, Gastropoda, Cirripedia, Decapoda. Their species composition and abundance depended on the timing of breeding of adult individuals, hydrological processes, and ecological condition of the waters.

Larval Polychaeta occurred in the coastal waters off the Heracles Peninsula throughout the year. In May–June and September–October, larvae of eurybiontic species from the families Spionidae (8 species) и Nereididae (5 species) predominated in abundance. In summer, larvae of the polychaete Nephys hombergii Savigny, 1818, which is characteristic of contaminated areas, were common in the plankton of the Bay of Sevastopol and Balaklava Bay. Larval Bivalvia were one of the permanent components of meroplankton and occurred all year round. The family Mytilidae (3 species) was represented most abundantly. In early spring and late autumn, mussel larvae Mytilus galloprovincialis Lamarck, 1819 predominated in abundance; in summer season, Mytilaster lineatus (Gmelin, 1791) and, in insignificant numbers, larvae Modiolus sp. and Cardiidae gen.sp were noted. In the summer–autumn period, larvae of the family Veneridae – Chamelea gallina (Linnaeus, 1758) were abundant. Larvae of two invasive species Anadara kagoshimensis (Tokunaga, 1906) and Mya arenaria also occurred in the study areas. A more diverse species composition and a higher abundance of mollusk larvae were recorded from open sea areas (st. 2, 4, 5), as compared to those in bays. Most Gastropoda breed in summer and, therefore, a significant increase in abundance of their larvae in coastal waters is observed from June to September. Veligers of eurybiont species Bittium reticulatum (Da Costa, 1778), Tricola pullus (Linnaeus, 1758) и Rissoidea (Rissoa parva (Da Costa, 1778), Rissoa sp.) members of the family were most abundant. Larvae of the invasive predatory mollusk Rapania venosa (Valenciennes, 1846) became common in the meroplankton from July to October. Larval Decapoda occurred from late May to October. The most abundant were: Diogenes pugilator (Roux, 1829), Clibanarius erythropus (Latreille, 1818), Hippolyte leptocerus (Heller, 1863) и Palaemon elegans Rathke, 1837. In open sea waters, which are free of anthropogenic impacts, the abundance of crab larvae (Pachygrapsus marmoratus (Fabricius, 1787), Xantho poressa (Olivi, 1792), Pilumnus hirtellus (Linnaeus, 1761) was by an order of magnitude higher than in bays. Cirripedia play an important role both in meroplankton and in
fouling of solid substrates. Larval *Amphibalanus improvisus* (Darwin, 1854) predominated in abundance in the waters of ports and near quays.

It was noted that the abundance of meroplankton in Balaklava Bay sharply decreased (up to 30 - 40 specimens • m$^{-3}$) during upwelling and, vice versa, increased 1700 specimens • m$^{-3}$ during downwelling events. The species that were carried into the bay with water masses at the plankton stage, in case of availability of suitable conditions for settlement, could have increased the biodiversity of this area.

Thus, in the waters with increased anthropogenic load the species diversity and abundance of meroplankton is reduced, the species sensitive to negative impacts vanish, and the dominance of eurybiontic species is observed.

The study of the sex structure of mussel aggregations and the identification of mechanisms of its formation and variability is an important phase in the analysis of the structural and functional characteristics of populations of this bivalve in the Black Sea. Previously, the sex ratio of the Black Sea mussel in all seasons of the year was 1:1 with a 1 – 3% proportion of hermaphrodites (Kudinsky & Shurova 1990; Pirkova 1994; Ivanov 2007). However, in recent years, some publications described the shifts in the sex structure of mussel populations towards the prevalence of both males and females (Shurova, 2001). It was noted that the males to females ratio in a mussel population depends both on the genetic mechanisms of sex formation and on the ecological conditions of the environment (Lee 2015). The ecological factors that have an effect on the sex ratio of bivalves can be as follow: being in a clump, limited water exchange, and accumulation of organic matter in the water column and bottom sediments (Shurova 2001).

The results of our studies show a shift in the sex structure towards increase in the number of males regardless of the size of bivalves and the habitat, with the proportion of hermaphrodites reaching 1–3%).

The maximum shift of the sex structure was noted by us in mussels with a shell length of 30 mm, collected at the st.1 in the most polluted part of the Bay of Sevastopol (Kuftarkova et al. 2011). In this bay, the prevalence of males over females was 7:1. Smaller in size bivalves are more sensitive to pollution of the marine environment. This masculinization of the bivalve population, occurring under the effect of pollutants, causes depression of some of the sex genes (Pirkova 1994).

The morphometric parameters of mussels have an adaptive value, and, for this reason, they are used as convenient marker indicators in assessing the condition of the surrounding aquatic environment. The mechanisms of adaptation to a technogenic pressure include an increase in convexity (D/L), and a change in the relative height (H/L) and thickness of shell (Dehta & Katalevsky 2000).

When studying the proportions of morphometric parameters in mussels of different size groups, we found no significant differences in the D/L index and thickness of shell. By a comparative analysis of the H/L index in mussels from different habitats, we showed that the maximum ratio values were in the bays with an increased technogenic load (st. 1, 8) (fig. 5). The H/L ratio in small-sized mussels was higher than in large-sized ones (30 mm: H/L – 0.65±0.02; 50 mm – 0.55±0.01). The proportions of morphometric traits in mussel populations reflect the levels of ecological comfort and technogenic load. Small-sized mussels are more sensitive to changes in the environment.

![Figure 5](image-url). Comparison of the H/L index in the mussel *M. galloprovincialis* with a shell length of 30 and 50 mm from various water areas.
Conclusion

1. The coastal waters off the Heracles Peninsula are characterized by upwelling water circulation. The frequency and intensity of upwelling events are higher in the waters off Balaklava as compared to those in the waters off Sevastopol.
2. The annual mean SST for the period 2000–2016 was by 2.7°C higher than in the first decade of the 20th century.
3. The maximum values of phytoplankton primary production are associated with the inner waters of the bays and with increased values of $T_{\text{water}}$ and $I_{\text{max}}$.
4. The qualitative and quantitative characteristics of phyto- and meroplankton in the waters off the Heracles Peninsula are determined by the hydrological and hydrochemical specifics of the area and by anthropogenic impacts.
5. The maximum shift of the sex structure in mussels towards the predominance of males was recorded from the most polluted area of the Bay of Sevastopol.
6. The H/L index of mussel shell was higher in the bivalves from the Bay of Sevastopol and Balaklava Bay than in open sea waters. Small-sized mussels are more sensitive to technogenic pollution.
7. The data on taxonomic structure of phyto- and meroplankton, sex ratio, and the morphometric parameters of mussels are the sensitive tools of ecological monitoring to assess the condition of the surrounding aquatic environment.

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