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Hydrophysical State of the Gulf of Feodosia in May 2015

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Abstract—Distribution of Sea of Azov water on the Crimean shelf and its penetration into the Gulf of Feodosia result in significant changes in the hydrophysical and hydrochemical structure of the water area. This inflow is also estimated as a major source of anthropogenic pollution in the region. At the same time, the Gulf of Feodosia is one of the least investigated areas of Russian Black Sea coast. The paper focuses on the hydrophysical structure of the Gulf of Feodosia and southeastern part of the Crimean shelf. The results of a field survey in May 2015 made it possible to reveal the presence of Sea of Azov water in the gulf and describe its thermohaline properties, along with the character of distribution. It is shown that contamination of Sea of Azov water in the gulf could mostly be determined by the synoptic dynamic processes in the area rather than by the seasonal variability of discharge in the Kerch Strait. The possible influence of the distribution of Sea of Azov water on the formation of cyclonic gyres in the coastal area of the region is indirectly confirmed by in situ measurements.

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INTRODUCTION

In coastal sea areas under the substantial influence of continental discharge, processes of different scales develop, caused by the interaction of different hydrophysical and hydrochemical characteristics of water masses. To a significant degree, these processes determine the functioning of marine and coastal ecosystems. In the Black Sea, one such zone is the southeastern coast of the Crimean Peninsula and the water area of the Gulf of Feodosia, which is significantly influenced by discharge from the Sea of Azov via the Kerch Strait, which creates a pronounced desalinated area [3]. The penetration of Sea of Azov waters into the Gulf of Feodosia leads to appreciable changes in the hydrological and hydrochemical structure of waters in the area. The period of maximum desalination of the gulf is May–June [2]. Under certain meteorological conditions, salinity in the gulf can fall to 13–14 PSU [4].

The mean interannual volume of Sea of Azov waters entering the Black Sea is estimated at 75 km^3/yr [5], and the maximum in the annual cycle has been noted in April–May. This is almost twice the discharge from the Dnieper and somewhat less than half the discharge from the Danube. The analogy to continental discharge is bolstered by the shape of the Kerch Strait, which is very similar to a river flowing into the Black Sea. An essential difference, however, is that the discharge through the Kerch Strait enters the Black Sea not as fresh water; it is the initially saline water from the Sea of Azov that is transformed in the strait, only 2–3 PSU less saline than the ambient waters of the Black Sea. Nevertheless, this discharge forms its own type of "plume" with a quite large linear scale distinctly visible in satellite images (Fig. 1a).

The most probable scenario for the behavior of Sea of Azov waters after they penetrate the outlet of the strait is a quite sharp turn to the west and propagation in a relatively narrow band along the coast of eastern Crimea toward the Gulf of Feodosia and beyond. Penetration of Sea of Azov waters—pressed to the coast by the Black Sea Rim Current (RC)—into the Gulf of Feodosia is often observed; to the right of the RC midstream an anticyclonic gyre forms, part of which occupies the water area of the gulf [7]. Coastal anticyclonic gyres in the Black Sea, as a rule, form between the RC midstream and the coast, where as a result of lateral velocity shear, an anticyclonic vorticity zone of the current field exists [10, 11]; however, for the area of the Gulf of Feodosia and east of it, where along with the RC there is also a discharge current from the Kerch Strait, this eddy-generation mechanism has been insufficiently studied. According to the data of [6], which is based on satellite data, in this region, not only are anticyclonic gyres frequency observed, but also cyclonic coastal gyres. Presumably, this may be related precisely to the cyclonic sign of velocity shear between the discharge current and the RC; however, this hypothesis requires confirmation with measurement data. In addition, the anticyclonic motion of waters along the entire water column from the surface to the

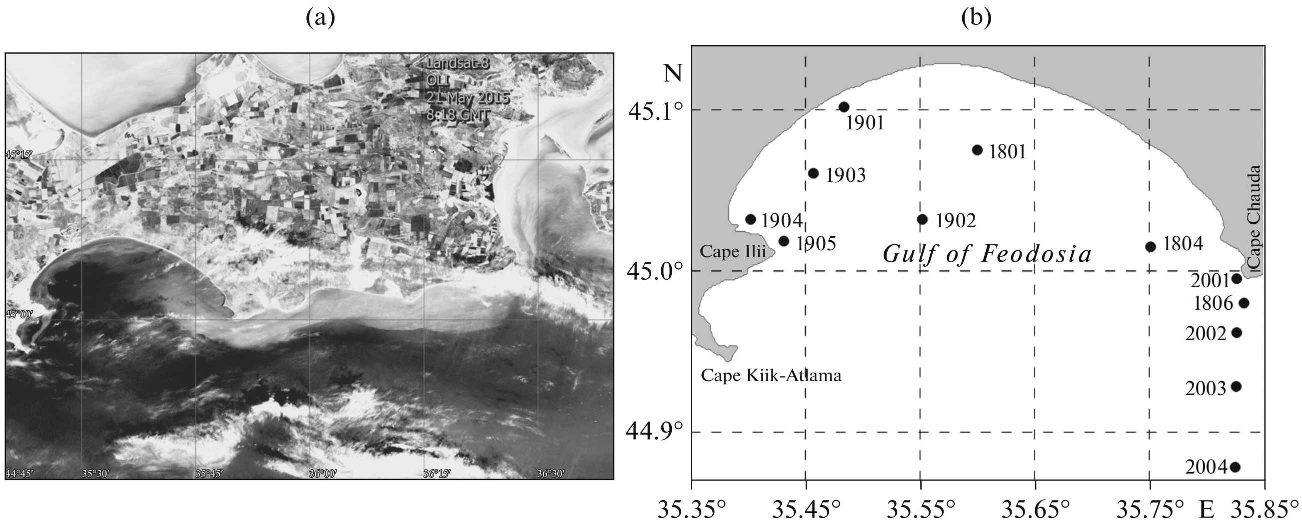

Fig. 1. Satellite image of investigated area from May 21, 2016. (a) Diagram of stations situated in the Gulf of Feodosia and adjacent shelf area during expedition of May 18–20, 2016 (b).

bottom was recorded in the southwestern part of the gulf by the authors of [1] based on CTD data.

It should be noted that area of the Gulf of Feodosia is one of the least studied areas of the Russian coast from the viewpoint of the water structure and dynamics, since for a long time it was used as a naval military test site, which limited the possibility of obtaining field data in expeditionary research [7]. At the same time, the water area of the Gulf of Feodosia, the coasts of which are home to large populated areas and recreational zones, has been subjected to a significant anthropogenic load. According to [9], the water area of the Gulf of Feodosia is one of the areas on the Crimean coast most polluted by dissolved petroleum products and organic substances. The authors of [8] point to excess MPCs of arsenic, zinc, lead, copper, and strontium in the gulf. For this region, there are two main sources of pollution: (1) a constantly active internal source: the port of Feodosia with its petroleum depot, near which maximum concentrations of heavy metals have been detected, and the concentration of dissolved petroleum products exceeds the conditional norm by 12–19 times; and (2) a remote external source related to advection of polluted waters from industrial regions on the shores of the Sea of Azov and the Kerch Strait into the water area of the gulf [9].

This article presents the results of field observations of the hydrological structure of the waters of the Gulf of Feodosia and the adjacent area of the shelf, obtained during an expedition of the Shirshov Institute of Oceanology of the Russian Academy of Sciences (SIO RAS) in May 2015. We discuss the physical processes determining the propagation of Sea of Azov waters in the Black Sea and compare newly obtained data with the results of similar earlier studies.

STUDY METHODS AND FIELD DATA

Measurements were organized as three one-day outings on the May 18, 19, and 20, 2015, in the water area of the Gulf of Feodosia, as well as in the area of the shelf of the southeastern coast of the Crimean Peninsula (Fig. 1b). Operations were conducted aboard the BPM-74 *Ashamba* of SIO RAS. In total, 12 hydrologic stations were placed in a sea depth range of 13–50 m, including a transect normal to the coast extending about 12 km in the area of Cape Chauda, consisting of four stations.

At each station, vertical CTD sounding of the water column was performed from the surface to the bottom using an SBE SeaCat19plus probe with a fixed measurement sampling rate of 4 Hz. In addition, the velocity and direction of sea currents on the transect from Cape Chauda were measured. Measurements were conducted on the May 20th outing at the four stations on the transect with an RDI RioGrande ADCP affixed to a special raft. During operations at a station, the raft with the attached device was lowered to the water, paid out from the vessel to the maximum possible distance (15–20 m), and maintained in such a position for 4–8 min. The directions and velocities of sea currents were recorded with an established cell size of 1 m. The vertical distributions of the current velocity components at each station were constructed from averaged series of ensembles (from 30 to 55) recorded by the device.

RESULTS AND DISCUSSION

Thermohaline structure. In the central and western parts of the gulf, a relatively homogeneous water structure was observed with salinity values of around

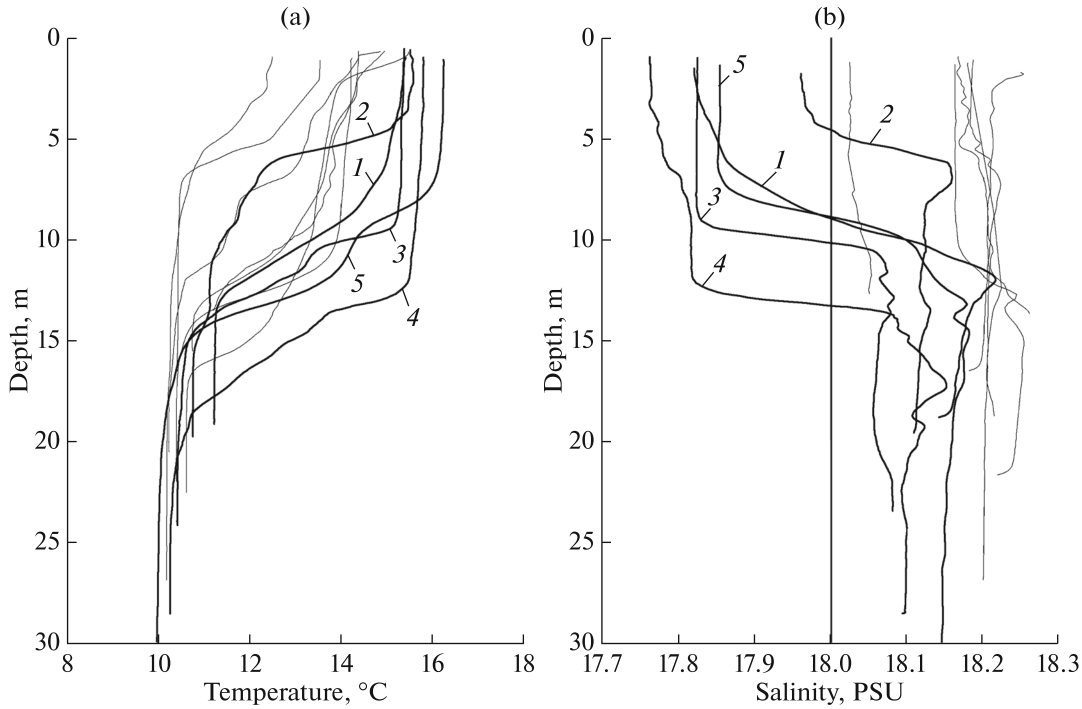

Fig. 2. Vertical profiles of temperature (a) and salinity (b) in Gulf of Feodosia according to CDT results May 18–20, 2015. Numerals denote stations: (*1*) 1804; (*2*) 1806; (*3*) 2002; (*4*) 2003; (*5*) 2004.

18.2 PSU (Fig. 2). The vertical temperature distribution in these areas was characterized by the presence of an upper thermal layer with maximum values from 16.2 to 12.5°C at the surface and a decrease down to 10°C toward the bottom. In the eastern part of the gulf and the adjacent shelf area, the vertical temperature and salinity gradients are more starkly pronounced, and the temperature values (up to 16°C at station 2004) in the eastern part of the gulf are higher than in the central and western parts. The observed "two-layer" vertical structure of the water column with a pronounced desalinated near-surface layer and a jump in temperature and salinity at its lower boundary is generally characteristic of coastal areas under the action of continental discharge.

Figure 3 shows the distributions of temperature *T* and salinity *S* on the transect normal to the beach, carried out from Cape Chauda to the south. The transect intersected the assumed zone of propagation of transformed Sea of Azov water in the area of the shelf to the east of the Gulf of Feodosia. Indeed, on the transect one can see the near-surface layer of decreased salinity (less than 18 PSU) and increased temperature (more than 15.5°C), which reaches a depth of 10–15 m. The "nucleus" of this layer can be referred to station 2003 at a distance of approximately 7.5 km from the coast, where the near-surface layer had the largest thickness; from here in the directions to and from the coast, salinity increased.

Based on analysis of the *T*, *S* curves for the waters of the Gulf of Feodosia and adjacent shelf zone (Fig. 4), it is possible to distinguish the main types of waters that formed the hydrological structure of the study area in the observation period. In [4], the salinity of the Black Sea surface water mass is determined within the limits from 18 to 18.4 PSU, whereas waters with a salinity of 17.8 PSU or lower pertain to the Black Sea coastal water mass (Fig. 4, *S* values less than 18 PSU), the main source of which on the Kerch–Taman shelf is Sea of Azov water. Generalizing the abovesaid, it is possible to state that in the measurement period, the area of most intense propagation of transformed Sea of Azov water was on the shelf to the east of the Gulf of Feodosia in the band limited by the 25 and 35 m isobaths. Entry of these waters into the eastern part of the Gulf of Feodosia has also been recorded, which led to the formation of appreciable horizontal salinity and temperature gradients in the near-surface layer of the latter.

The above-mentioned hydrological structure of the Gulf of Feodosia waters has similarities to and differences from another case, described in the literature, of penetration of Sea of Azov waters into the gulf in winter 2006–2007 [7]. In both cases, in gulf waters (predominantly in its eastern part), a pronounced surface layer of decreased salinity formed. However, whereas in December 2006 the difference in the salinity values between the two types of waters exceeded 2 PSU [7], in May 2015, it was only tenths of a PSU. The vertical temperature distribution in the gulf in

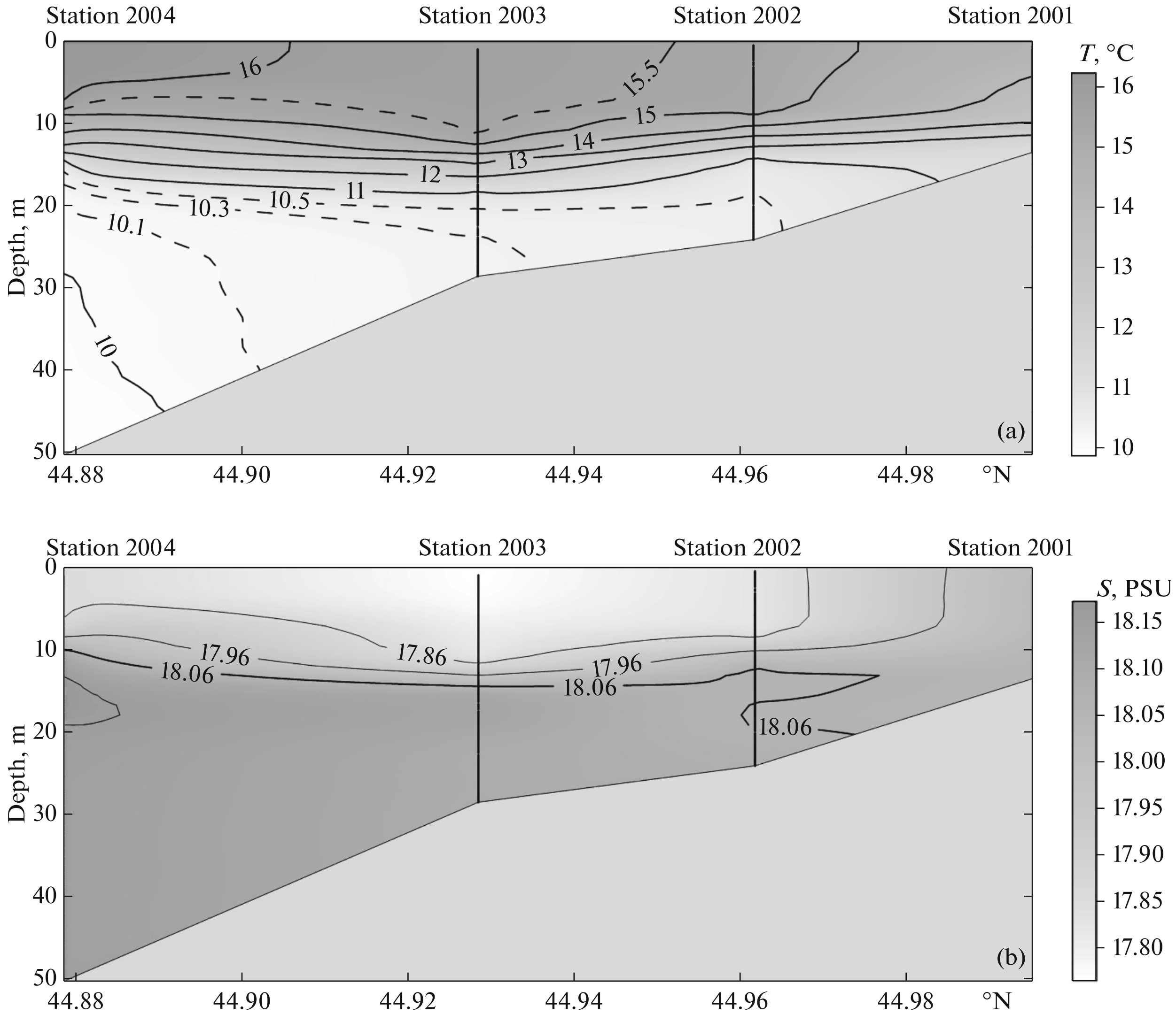

Fig. 3. Vertical distributions of temperature (a) and salinity (b) on transect normal to coast from Cape Chauda May 20, 2015.

December 2006 was characterized by the presence of a layer of decreased values in surface waters with a thickness of 5 to 15 m [7] and by a temperature inversion in the underlying layer. Conversely, in May 2015, in the upper mixed layer, the temperature maximum was noted (Fig. 2a). This should be related to the fact that in December, waters in the shallow Sea of Azov and Kerch Striat are colder than Black Sea waters, and in May, they are warmer. It should be kept in mind that, according to climate data, the largest discharge from the Kerch Strait is observed in May–June and not in winter. Thus, apparently, the content of Sea of Azov waters in the Gulf of Feodosia is mainly determined not by the seasonal cycle, but by synoptic-scale dynamic processes, the position of the discharge current, and the degree of its penetration into the waters of the gulf.

Water circulation. According to ADCP data, on the transect from Cape Chauda, overall motion of water masses on the whole from east to west was observed (Fig. 5). The longshore (zonal) component of the current velocity was in all cases directed to the west and reached values of 43 cm/s; the component transverse to the coast (meridional component) varied from –9 to 22 cm/s. In the current structure on the transect, the presence of a pronounced near-surface current should be noted on the whole, whereas the meridional component changes sign at the lower boundary of this layer. Thus, the overall transfer within this layer was directed into the Gulf of Feodosia, whereas in the layers of the water column below the zero isotach, the transfer was directed toward the open sea. According to the aforementioned CTD results, the location of the jump in density approximately corresponds to the position of the zero isotach of the meridional current component. Thus, the current velocity measurement data agree with the notion of transformed Sea of Azov waters penetrating into the Gulf of Feodosia in the upper 15 m layer of the sea.

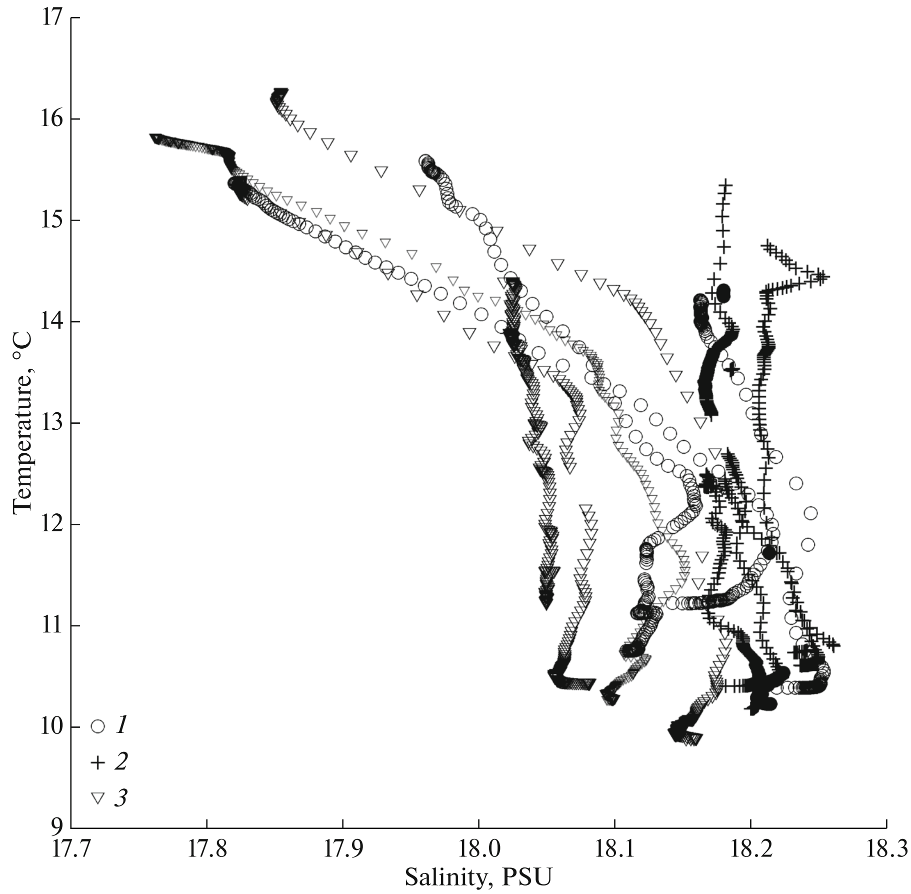

Fig. 4. *T,S* curves of waters of Gulf of Feodosia and adjacent shelf area from vertical CTD data at stations: (*1*) eastern part of gulf May 18, 2017; (*2*) western and central parts of gulf May 19, 2015; (*3*) transect from Cape Chauda May 20, 2017.

From the CTD data, we also calculated the geostrophic current velocities on the transect from Cape Chauda with respect to the 13 m horizon. The observed character of the density distribution on the transect (Fig. 6a) points to the existence of two differently directed geostrophic flows in the near-surface layer (Fig. 6b). The geostrophic velocity in the part of the near-surface layer between the coast and the 30–35 m isobath (i.e., approximately to the axis of the discharge flow) was directed from east to west, but it turned in the opposite direction seaward of this area, which speaks to the cyclonic character of overall vorticity south of the axis of the discharge flow. Direct current velocity measurements apparently confirm this (Fig. 7): the velocity of the longshore current first increases with distance from the coast, reaching maximum values at a distance of around 4 km from the latter, and then decreases toward the continental slope, shifting the sign of the cyclone.

CONCLUSIONS

Based on direct measurement data, the presence of the transformed Sea of Azov waters was observed in the area of the Gulf of Feodosia and on the adjacent shelf area east of the gulf in May 2015. The presence of these waters was localized in the upper 15 m layer of the sea in a band whose axis was 7–8 km from the coast east of the Gulf of Feodosia, as well as in the eastern sector of the gulf itself. Despite the season of maximum discharge through the Kerch Strait, the thermohaline manifestation of Sea of Azov waters in the study area was less pronounced than that observed in winter 2006 in an earlier published detailed study of the distribution of Sea of Azov waters in the area of the Gulf of Feodosia. It can be concluded that the content of these waters in the Gulf of Feodosia is mainly determined by synoptic-scale dynamic processes and not by the seasonal variations of discharge. Direct current velocity measurements, as well as geostrophic estimates, indicate the existence of a longshore current carrying Sea of Azov waters toward the west in the upper 15 m layer; as well, this current, at least in the measurement period, apparently "overtook" the RC; cyclonic velocity shear was observed on its southern periphery. Thus, there is indirect confirmation of the idea that Sea of Azov discharge may be responsible for the frequent generation of coastal cyclonic gyres in this

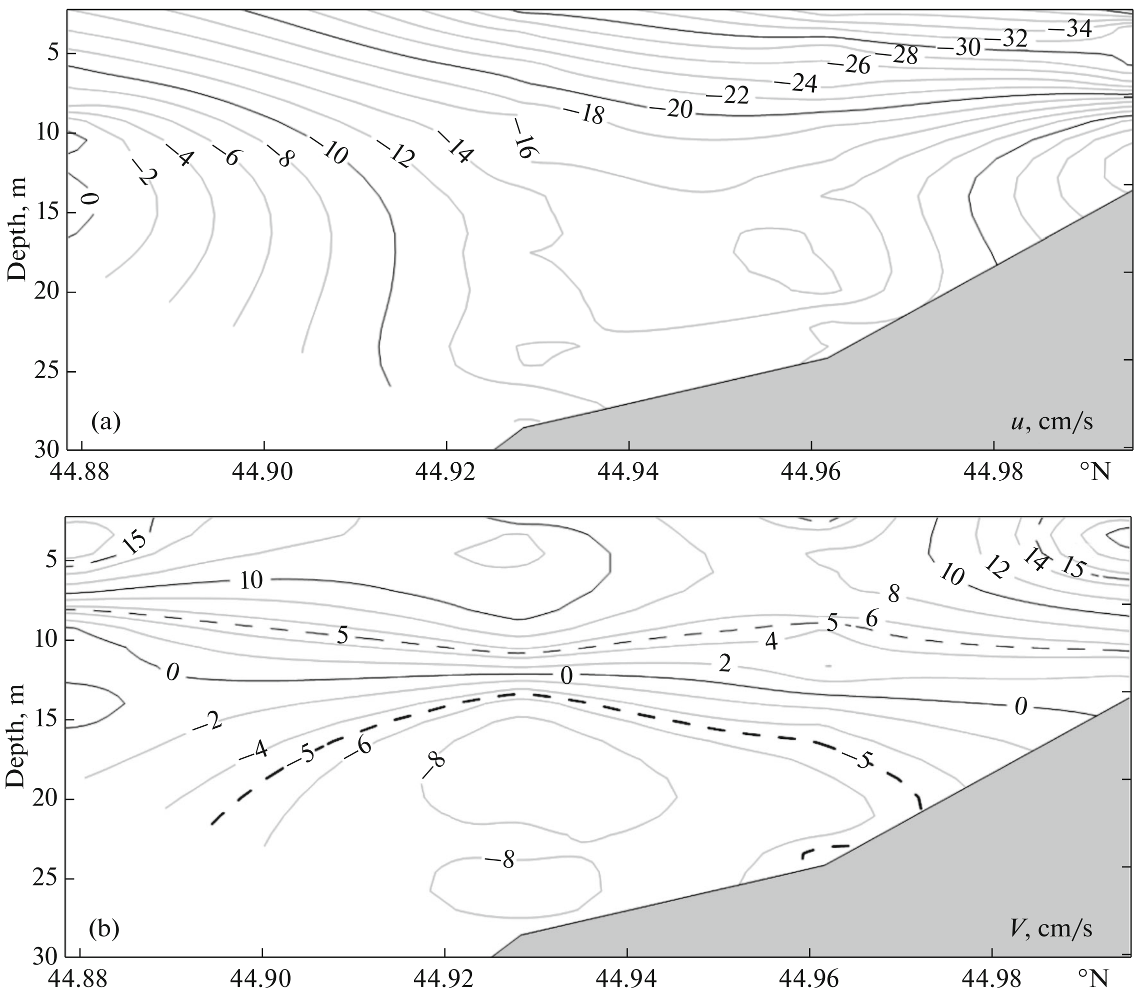

Fig. 5. Vertical distribution of values of zonal (a) and meridional (b) components of current velocity from ADCP measurement data on meridional transect from Cape Chauda (May 20, 2015).

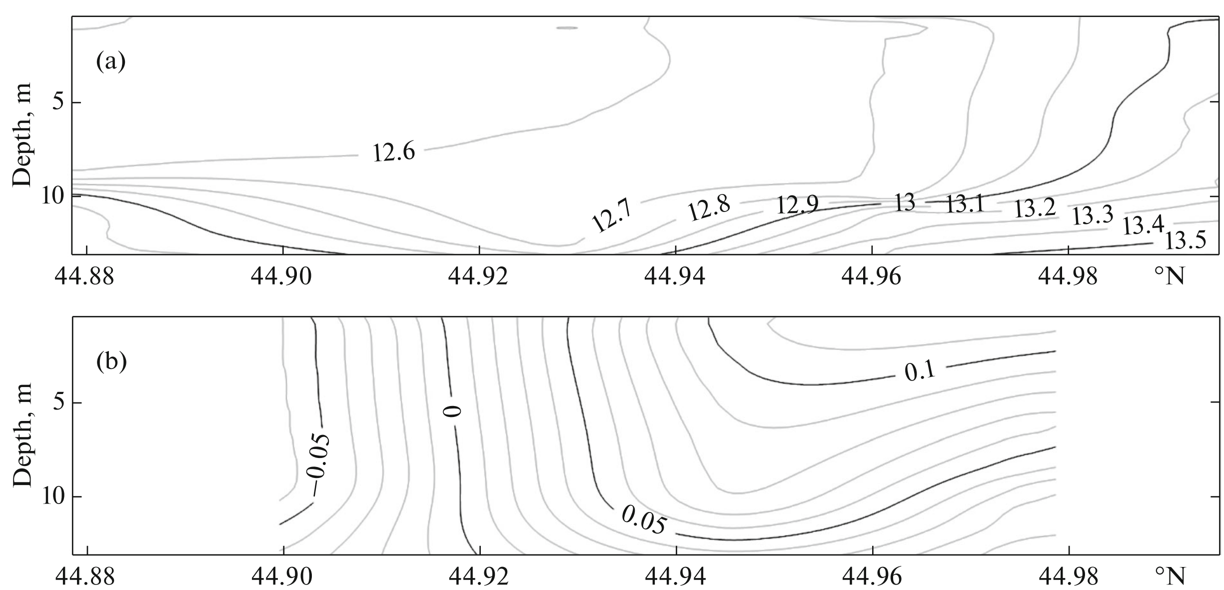

Fig. 6. Vertical distribution of values of conditional density (kg/m^3) (a) and geostrophic component of zonal current velocity (m/s) (b) from surface to depth of 13 m on meridional transect from Cape Chauda (May 20, 2015).

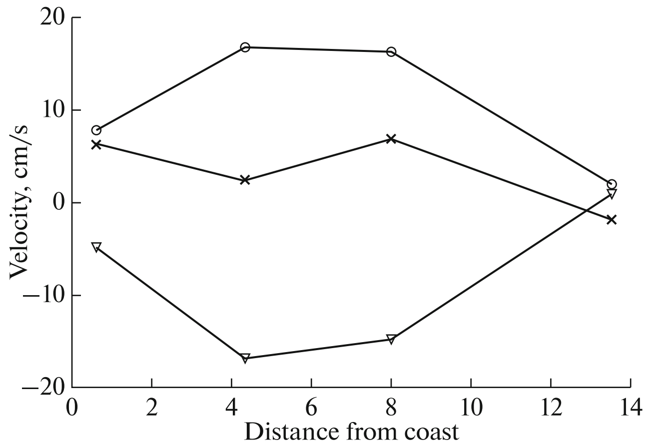

Fig. 7. Values of current velocity (circles) and its zonal (triangles, positive direction—east) and meridional (crosses, positive direction—north) components at depth of 10 m as function of distance from shore according to ADCP measurement data on meridional transect from Cape Chauda (May 20, 2015).

area. However, a more careful analysis and solid confirmation of this hypothesis require longer-term measurements.

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