Water Circulation in the Northern Black Sea in Summer 2016 (Based on the Data Obtained in the 87th Cruise of the R/V Professor Vodyanitsky)

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The present work represents the results of water circulation in the northern Black Sea analyzed based on the data of the surveys carried out in the 87th cruise of R/V Professor Vodyanitsky in July 2016. It is shown that during the survey the westward flows being the Rim Current (RC) manifestation are predominant within the studied water area. Based on the survey data, the latitudinal location of the Rim Current geostrophical deep stream is close to its climatic position. In the western part of the polygon, the Rim Current is divided into three branches. The northern branch is located over the shelf, the central one – over the continental slope and the southern one – over the deep-sea regions. The Sevastopol anticyclone is characterized by extremely asymmetric vertical development: its northern periphery over the shelf is weak, whereas the southern periphery over the continental slope is intensive. In the central part of the polygon the Rim Current intensifies, at that one intensive stream is traced. In the eastern part of the polygon two branches of the Rim Current are observed: the intensive northern one over the continental slope and the coastal shelf, and the one located closer to the deep-sea regions (its velocity is rather low and it weakens moving eastward). In the upper layer to the east off Cape Ai-Todor, the anticyclonic gyre is observed; whereas within the 50–100 m below it, the cyclonic turn of the currents is revealed.

Keywords: the Black Sea, the Rim Current, Sevastopol anticyclonic gyre, water circulation, spatial-temporal variability.

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Introduction. History of the oceanographic studies in the Black Sea indicates that the most intensive works in this direction were carried out within the period from the second half of the 70s until about the middle of the 90s [1]. Marine Hydrophysical Institute (MHI) of the Academy of Sciences of the Ukrainian SSR made a dominant contribution to obtaining experimental data on the Black Sea. Oceanographic surveys were carried out at the MHI research vessels Akademik Vernadsky, Mikhail Lomonosov and Professor Kolesnikov [2–4]. The second half of the 80's and early 90's was particularly effective. Then the research was performed under such international programs as HydroBlack, CoMSBlack, NATO TU Black Sea, etc. [5–10].

After 1995, due to economic and financial difficulties, large-scale synoptic surveys in the Black Sea were stopped. Against the background of a reduction in the number of expeditionary measurements, drifting technologies began to play an important role. The largest number of drifting experiments to study the Black Sea currents was carried out using the LOBAN (light one-time buoy with automatic navigation) type buoys, Lagrangian SVP and SVP-B drifters and drifting (Argo profiling floats) Argo buoy [11–14].

The MHI oceanographic studies activated starting from the summer of 2007, when the research began on small-tonnage vessels R/V Experiment, R/V Sapphire and SHSV Rioni. In 2010, after a long break, R/V Professor Vodyanitsky came into commission. The works were carried out mainly in the coastal areas of the northwestern shelf, Zmeinyy Island, the Danube estuary, in the water areas adjacent to the Belgorod-Dniester and Dnipro-Bug estuaries in the northern part of the Chersonese-Bosporus secular section, near the Sevastopol anticyclone [15–17]. Due to the small size of the vessels, the performance of the work was largely dependent on the weather conditions. As a rule, the surveys were carried out irregularly, only under a favorable wind-wave regime, mainly in the warm season, and covered small water areas. As a result, a large number of questions appeared while interpreting the distributions of actual hydrological parameters at small ranges and comparing them with the climatic fields obtained from the archival databases of average monthly data with a large spatial grid step. For the sea surface, the acuteness of the problem was reduced by the attraction of high spatio-temporal resolution satellite data. Analysis of the simulation of the Black Sea currents by satellite data is most fully presented in [18]. However, satellite data does not provide information on the deep layers of the sea, which can only be obtained by contact methods during the survey. In this regard, when planning expeditionary research for 2016, it was proposed to resume the regular implementation of large-scale oceanographic surveys, allowing to cover the measurement of large areas of the Black Sea for a relatively short time period.

The first survey was carried out in July 2016 in the 87th cruise of R/V Professor Vodyanitsky. The studies were performed within the framework of the FSBSI MHI State Target on the projects "Fundamental Oceanology", "Climate" and "Operational Oceanography". The main task of hydrological works was to obtain experimental data on the distribution of current velocities and thermohaline characteristics aimed to interpret the formation conditions of hydrochemical, optical and biological characteristics of sea water. It should be noted that in the course of this survey, instrumental measurements of currents were first performed on a vast water area covering the shelf and deep-water part of the sea.

In the present work, the water circulation analysis results are presented based on the survey material. The structures of the currents obtained by the dynamic method from hydrological measurements were compared, according to instrumental measurements and model calculations [19].

Materials and methods. The works were carried out from June 30 to July 18, 2016 in the northern Black Sea within the economic zone of Russia. The layout and numbers of the stations and sections of the 87th cruise of R/V Professor Vodyanitsky are shown in Fig. 1. At each station, the hydrological characteristics from the surface to the bottom were measured using the CTD SBE 911plus complex, the zonal and meridional components of the current velocity in the upper layer from 5–10 to 300 m – using the Acoustic Doppler Current Profiler (ADCP).

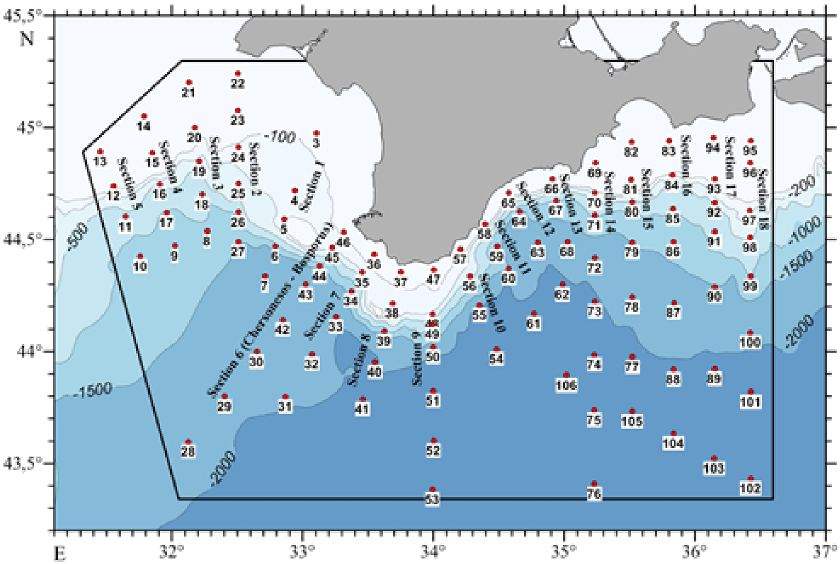

Fig. 1. The layout and numbers of the stations and sections of the 87th cruise of R/V Professor Vodyanitsky. Dotted lines are the main isobaths; the stations are marked with red dots

To compare the structure of the currents obtained from the expedition materials to the climatic circulation of water, the mean annual temperature and salinity data with monthly averaging from the array of hydrological measurements of the MHI ocean data bank were used [20]. The geostrophic velocities were calculated with respect to the 300 dbar surface based on survey and climatic data. Distributions of vectors of geostrophic currents at 1 m horizon and instrumentally measured currents at 10 m horizon were compared with the distributions of model current vectors on the surface from the array [19]. This array contains the average daily values of the current velocity components at the nodes of the (regular grid with 0.125 × 0.125° step). можно короче – regular 0.125 × 0.125° grid

To construct a map of vectors, the model velocity values at the nodes closest to the coordinates of the hydrological stations for the time period of measurements at these stations were chosen. Then the values of the velocities of model, geostrophic and instrumentally measured currents were reduced to the nodes of a regular 0.1 × × 0.1° grid. After the spatial distributions of the vectors of these currents were compared at the polygon. Additionally, the structure of zonal currents was compared by different methods on meridional profiles with a discreteness of 0.5° longitude between 32 and 36.5°E. In order to estimate the consistency of the horizontal fields of the zonal and meridional components of the current rates between these fields obtained by different methods, the coefficients of the linear correlation were calculated.

Main results. According to the climatic data [20], the survey period of the 87th cruise of the R/V Professor Vodyanitsky (July) is characterized by the following features of the water circulation. The central part of the research area is crossed by the current of the western direction – the Black Sea Rim Current (RC) (Fig. 2). In the insets of Fig. 2 the graphs of the climatic seasonal cycle of the zonal geostrophic velocity in the RC core and its latitudinal position on the meridians 31.5° (*1*), 32.5° (*2*), 34° (*3*), 34.25° (*4*), 36.25°E (*5*) are shown. It can be seen that in the western part of the polygon (meridians 1, 2) in the seasonal cycle from April to September, the velocities in the RC core decrease, i. e. the time of observations falls on the period of intensive seasonal RC weakening. Climatic velocities in the RC core during this period are 12–13 cm/s and 13–14 cm/s, respectively (Fig. 2, insets). In the central part of the polygon (meridians 3, 4) there is a general amplification of RC, while in the seasonal cycle in July-August the velocities in the RC core reach a minimum and are 16–17 and 12–13 cm/s, respectively.

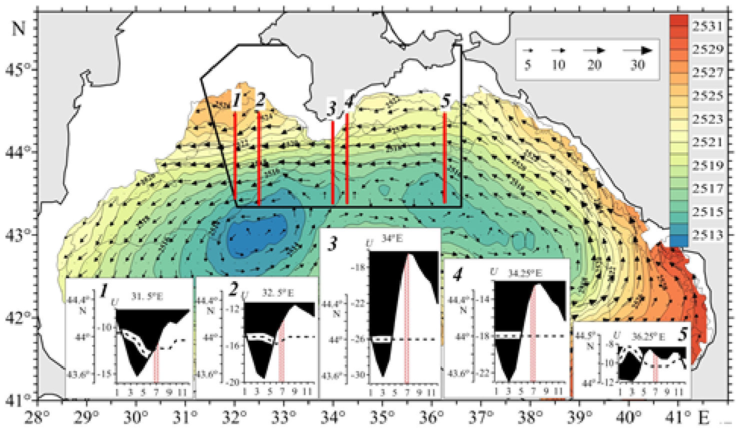

Fig. 2. Dynamic topography and vectors of geostrophic currents (cm/s) on the horizon of 1 m relative to 300 dbar in July, according to the data of the MHI ocean data bank [15]. In the inset – the climatic seasonal cycle of the zonal component of the geostrophic velocity *U* in the RC core (black fill) and the position of the core (dashed lines) on the meridians *1–5* (red lines), the survey period is highlighted by red shading

In the east of the survey area, closer to the Kerch Strait (meridian 5) the RC weakens. During the research, the climatic velocities in its core do not exceed 8–9 cm/s. The latitudinal position of the RC core changes as it moves eastward: there is a shift to the north, qualitatively reflecting the features of the bottom topography. The climatic latitude of the RC core on the meridians 1–5 in July is 43.85°; 43.9°; 44 °; 44° and 44.2°N, respectively.

Water circulation analysis based on the survey data showed that, according to the results of geostrophic and model calculations and instrumental measurements, the water circulation at the polygon is mainly represented by western direction flows (RC), while their velocity significantly varied in space (Fig. 3), which qualitatively agrees with climatic data. The latitudinal position of the geostrophic RC core, coinciding with the zonal velocity maximum, according to the survey data coincided with its climatic position and at meridians 2–5 was 43.9°; 43.8°; 44° and 43.9°N, respectively (Fig. 4).

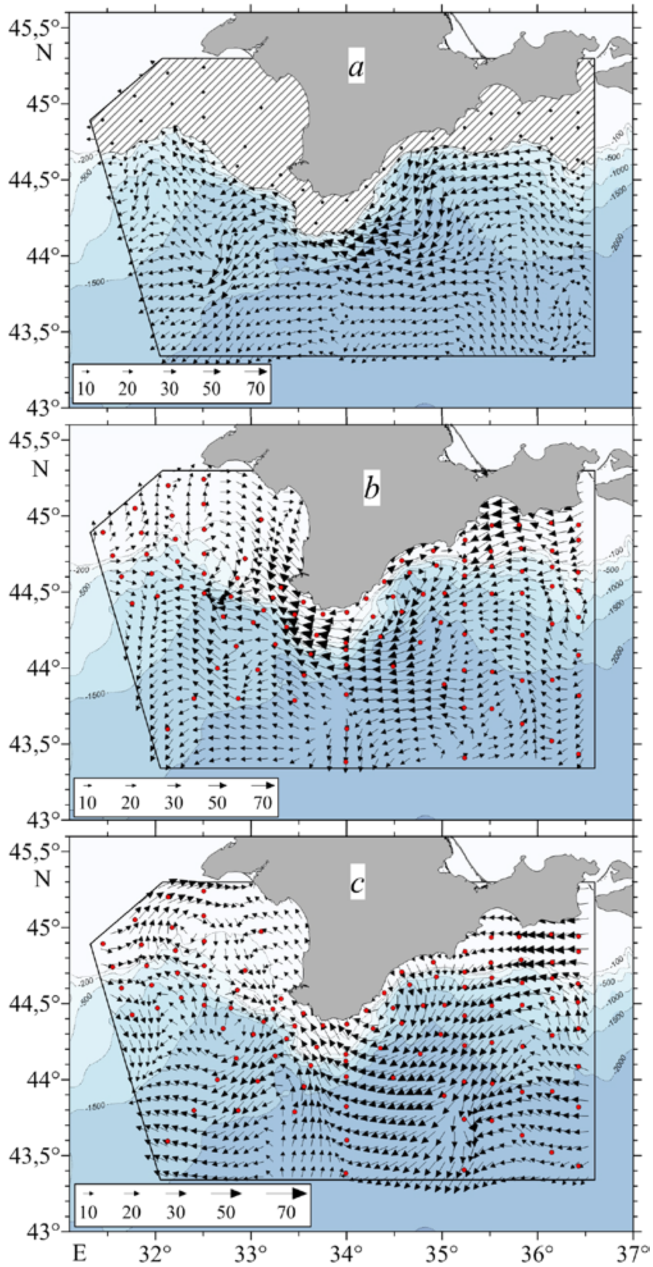

Fig. 3. Vectors of the currents (cm/s): the geostrophic ones at 1 m horizon relative to 300 dbar from survey data (*a*), the instrumentally measured – at 10 m (*b*) horizon, the modeled – on the surface (*c*)

At the same time, there were some differences in the water dynamics from the climate pattern. They may be related to the interannual or synoptic variability of water circulation. According to the survey, the RC strongly meandered, sometimes dividing into separate branches. In places, the RC meanders formed anticyclonic and cyclonic gyres, which were manifested as multidirectional flows at meridional distributions of zonal velocity (Fig. 4).

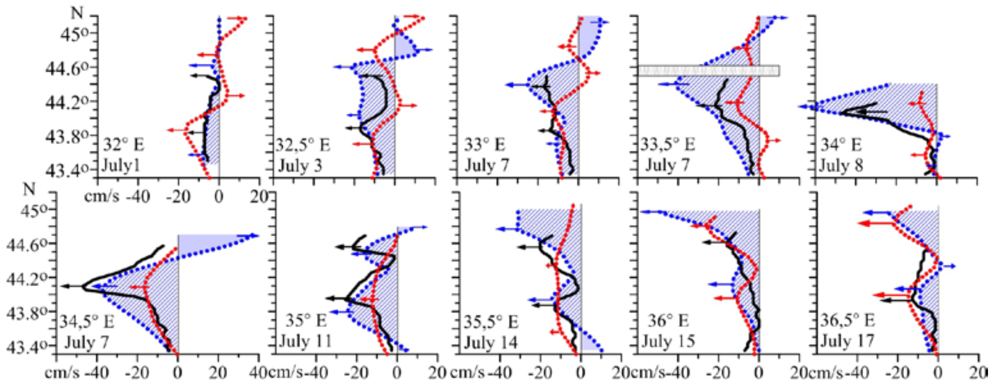

Fig. 4. Distributions of the zonal component of the current velocity along different meridians: the geostrophic one – black solid line, the instrumentally measured – blue dotted line, the model – red dotted line, arrows denote the stream cores

The RC division into individual branches is most clearly expressed in the western part of the polygon (Fig. 3). To the south-west of Heraclean Peninsula, during the instrumental measurements the northern coastal branch, following in a northwesterly direction, was clearly visible above the shelf. According to the model calculations, it was less pronounced. Geostrophic calculations, because of the exclusion of the shelf zone with depths of less than 300 m, did not fix the coastal branch. Another part of the RC waters moved westward along the continental slope. In the area of 32–33°E a separate jet was formed. It was called the central branch of the RC. This branch was traced in the form of an extremum on the zonal velocity distributions along meridians 32 and 32.5°E (Fig. 4) and represented the southern periphery of the anticyclonic gyre. According to the established terminology, this anticyclone was called the Sevastopol (SA) [1, 5, 21, 22]. It was located above the shelf and continental slope between the isobaths of 100 and 1500 m. According to instrumental measurements, the SA was well manifested on the distributions of the current vectors (Fig. 3, *b*) and zonal velocity along 32; 32.5 and 33°E (Fig. 4). Geostrophic calculations fixed only the southern periphery of this gyre (Fig. 3, *a*). According to the model data to the west of the Crimean Peninsula, two anticyclonic gyres were distinguished, while the position of each of them was significantly different from the SA position by the instrumental data and geostrophic calculations. One gyre was located on the shelf above the 50–100 m isobaths between 32 and 32.5°E, the second – in the area of the continental slope above the 500 and 1500 m isobaths between 32.5 and 33°E (Fig. 3, *c*). There was a discrepancy between the zonal velocity extrema position in instrumental measurements and model data on the meridional profiles (Fig. 4). Thus, according to instrumental data and according to the model the water circulation of in the SA area was reproduced in different ways.

To the northeast of the SA in shallow water, approximately at the longitude of the Cape Evpatoriyskiy, the northern coastal branch of the RC interacted with the eastern periphery of the SA. On the map of the distribution of model vectors in this area, a slightly pronounced cyclonic gyre was observed (Fig. 3, *c*). The distribution of zonal velocities along the 33°E showed two different directions of the stream, indicating a cyclonic direction of currents in this area (Fig. 4). Because of the large distance between stations in this region, the instrumental measurements did not fix this cyclonic gyre (Fig. 3, *b*).

To the south of the Sevastopol anticyclone over the depths of 500–1500 m, a cyclonic meandering of the RC was observed for all data types (Fig. 3). Its northern periphery simultaneously served as the southern boundary of the SA.

In the southwestern part of the polygon, above the great depths, an increase in the current velocity was recorded. It was manifested as another extremum at the meridional distributions of the zonal velocity, which indicated the presence of another RC branch – the southern one (Fig. 3, 4). Its eastern extension was monitored up to the depths of the southeast coast of the Crimea.

In the central part of the polygon to the south of the Crimean coasts, the overall RC intensification was observed for all data types (Fig. 3), which corresponded to the climatic RC strengthening in this area (Fig. 2). According to the geostrophic calculations and instrumental measurements in the meridional structure of the RC at 34°E a single intense jet was clearly pronounced (Fig. 4). According to the model calculations, two weak extrema of the zonal component of the velocity with a noticeable enhancement of the meridional component were manifested here (Fig. 3, *c*).

Eastward of 35°E two RC branches were monitored in the instrumental and model data: the intensive one – coastal zone above the shelf and the continental slope and the weaker one – in the seaward part of the polygon (Fig. 3, *b*, 3, *c*, 4). Between the Cape Ai-Todor and Meganom over the shelf and the continental slope, an anticyclonic gyre was observed. It was most clearly expressed from the data of instrumental measurements (Fig. 3, *b*, 4). According to geostrophic and model calculations only its southeastern periphery was distinguished (Fig. 3, *a*, 3, *c*). Another notable element of circulation, obtained from the field data and well agreed with instrumental measurements (Fig. 3, *b*), was the cyclonic gyre in the southeast of the survey area. On the velocity distribution along 35.5°E this gyre was manifested in the form of multidirectional flows in the southern part of the profile (Fig. 4).

The analysis above showed that the results of instrumental measurements of currents, geostrophic and model calculations do not always bear mutual respondence. Quantitative estimates of the consistency of the horizontal fields of the *U* zonal and *V* meridional current velocity components showed that the values of the *R* correlation coefficients between the velocities according to instrumental measurements and geostrophic calculations are as follows: for the zonal component – 0.84, for the meridional one –0.52 (Fig. 5, *a*, 5, *d*). Consistency between the model and geostrophic velocities decreases. The *R* values for the zonal component are 0.47, for the meridional one – 0.5 (Fig. 5, *b*, 5, *e*). Consistency between the zonal velocity components slightly increases according to instrumental measurements and model calculations

(R ~ 0.57) (Fig. 5, *c*) and practically does not exist between the meridional components (R ~ 0.36) (Fig. 5, *f*). Thus, the consistency between the velocities of currents in accordance to the instrumental measurements and geostrophic calculations is much higher than according to other methods. At the same time, geostrophic calculations, in contrast to instrumental data, due to integral approach roughly resolve the vertical structure of the currents. In addition, the dynamic method is not applicable to the calculation of currents in shallow water. It should also be noted that the horizontal distributions of the current vectors were obtained by an objective interpolation of actual values in the regular grid nodes with the range exceeding the mean distance between the actual sections. As a result, some features of the general circulation scheme can be smoothed out on the maps.

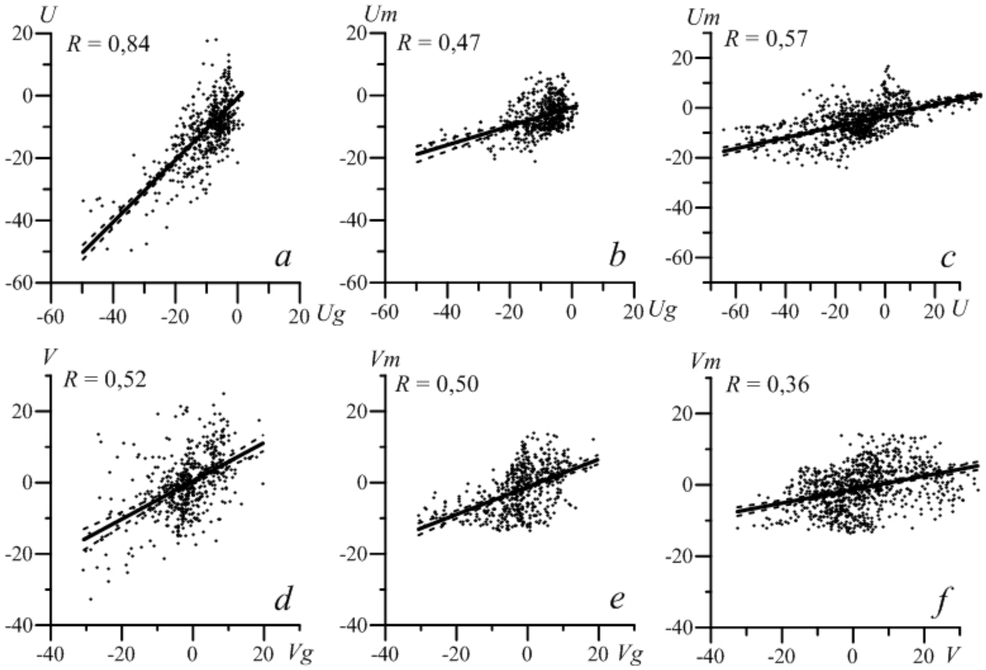

Fig. 5. Graphs of the linear relationship between the current velocities according to the instrumental measurements (*U, V*) and geostrophic calculations (*Ug, Vg*) (*a*, *d*), model (*Um, Vm*) and geostrophic calculations (*b, e*), instrumental measurements and model calculations (*c, f*). The zonal component is fragments *a* – *c*, the meridional one – *d* – *f*. Dashed lines mark the boundaries of the 95 % confidence interval

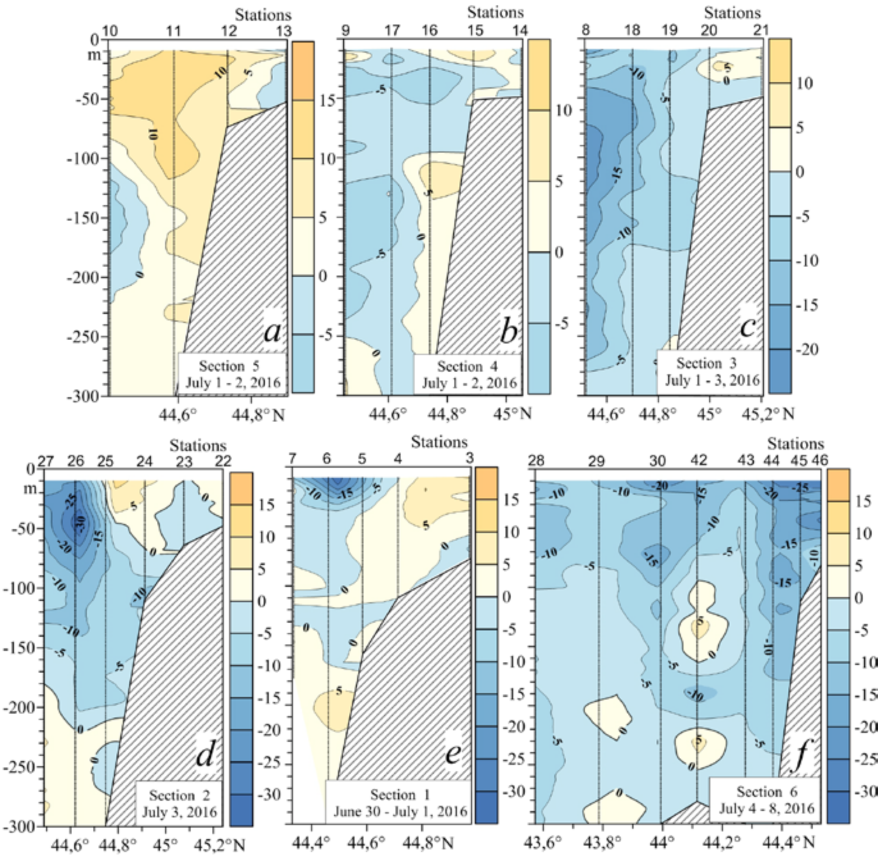

Fig. 6. Vertical distributions of zonal velocities of the instrumentally measured currents (cm/s) in the 0–300 m layer on the sections 5 (*a*), 4 (*b*), 3 (*c*), 2 (*d*), 1 (*e*) and 6 (*f*). Position of the sections is shown in Fig. 1

With reference to the above mentioned, the vertical structure of the main circulation elements on each of the sections (see Fig. 6–8) is specified below according to instrumental measurements of currents. In accordance with the horizontal distribution of the current vectors (Fig. 3, *b*), southwest of the Heraklean Peninsula, the separation of the RC flow into separate branches occurred. On the section 7 (Fig. 7, *a*) and 6 (Chersonese – Bosporus) (Fig. 6, *f*), made in this area, two RC branches were clearly distinguished. A more intense northern branch passed over the coastal shelf and the continental slope. The maximum of its velocity was fixed above the shelf in the surface layer and was 45 cm/s (Fig. 7, *a*) on the section 7 and 35 cm/s – on the section 6 (Fig. 6, *f*). The velocity values decreased rapidly with depth and at the bottom on the shelf did not exceed 10–15 cm/s. Above the continental slope of the 10 cm/s isotach, the northern RC branch was monitored up to 175 m in the section 6 and up to 100–110 m in the section 7. The southern RC branch was recorded in the sea part of the sections with the velocity cores up to 25 cm/s in the upper 15 m layer in the section 6 and up to 15 cm/s in the 50–70 m layer in the section 7. The vertical thickness of this branch, according to the 10 cm/s isotach was 100–120 m.

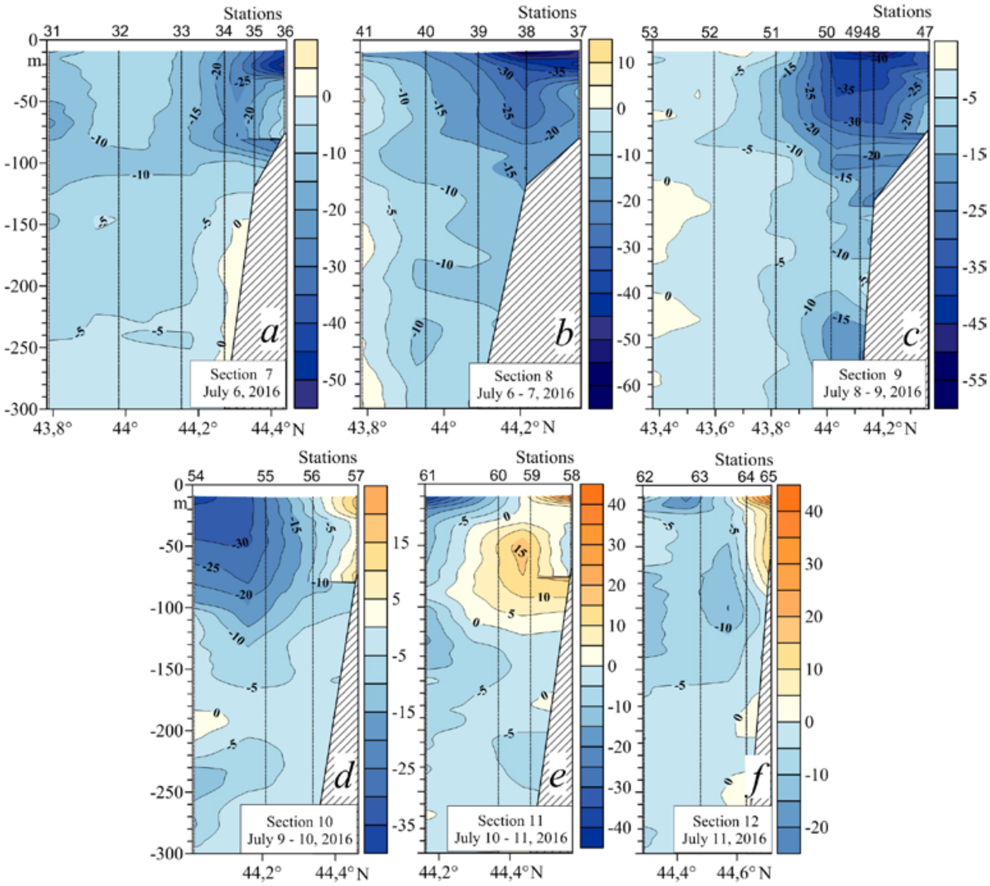

Fig. 7. The same as on Fig.6 in the sections 7 (*a*), 8 (*b*), 9 (*c*), 10 (*d*), 11 (*e*), 12 (*f*)

In the western sections 1–3, having a smaller extent in the seaward direction, only the central RC branch, located in their southern part (Fig. 6, *c* – *e*), was fixed. Above the shelf and the continental slope, the eastern direction stream was observed. Its maximum velocity was located in the upper 20 m layer and did not exceed 5–10 cm/s. These sections crossed the Sevastopol anticyclone (Fig. 3, *b*). The weak eastern coastal stream was its northern periphery. The southern SA periphery was the central RC branch. In the section 1, the core of its velocity (15–20 cm/s) was located in the upper 20 m layer. Along the 10 cm/s isotach, this branch was traced to a depth of no more than 30 m (Fig. 6, *e*). The velocity core of the central RC branch (25–35 cm/s) was located in the 20–60 m layer in the section 2 (Fig. 6, *d*). Along this 10 cm/s isotope, this branch was monitored to the depths of 125–140 m. In the section 3 its velocity maximum weakened to 20 cm/s and deepened to 75–130 m, while at 10 cm/s it was observed up to a depth of 270 m (Fig. 6, *c*). The deepening of the central RC branch maximum velocity indicates that the SA had an asymmetric vertical power with a poorly developed northern periphery.

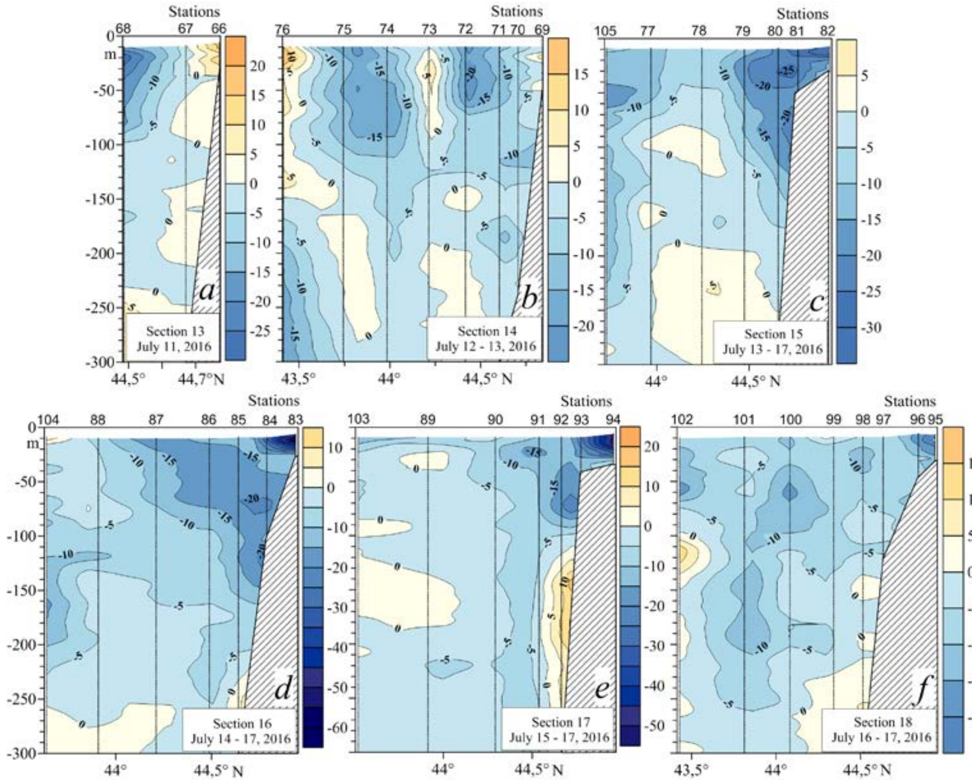

Fig. 8. The same as on Fig. 7 in the sections 13 (*a*), 14 (*b*), 15 (*c*), 16 (*d*), 17 (*e*), 18 (*f*)

In the extreme western point of the polygon (the sections 4 and 5), further weakening of the currents was noted (Fig. 6, *a*, 6, *b*). In the section 4 (Fig. 6, *b*), the westward stream occupied the greater part of the cross-sectional area with two weak velocity cores (up to 5 cm/s) at the depths of 25–50 m and 100–200 m. Above the coastal shelf in the surface layer and in the 100–130 m layer of the continental slope, weak eastward streams (up to 5–10 cm/s) were monitored. In the section 5, the RC stream appeared in its southern part in the form of a weak velocity core (up to 5 cm/s) in the 100–200 m layer (Fig. 6, *a*). The main part of the section was occupied by the eastward stream with a blurred velocity core (up to 10 cm/s) in the upper 100 m layer. A weak westward current (up to 5 cm/s) was observed on the shelf deeper than 15 m, which indicated the presence of a cyclonic meander here.

In the central part of the polygon (the sections 8–10), the total RC intensification was recorded, while the only one intense RC jet was observed within the sections (Fig. 7, *b* – *d*). In the sections 8 and 9 it was retained against the shelf boundary. The maximum velocities in the RC core reached 60–65 cm/s. Somewhat in the eastern direction, in the section 10, the velocities in the core decreased to 40 cm/s, and the core itself shifted to the seaward part. The maximum current depth along the 10 cm/s isotach was observed in the section 8 and reached almost 250 m. To the east, it gradually decreased to 175 m in the section 9 and to 125 m in the section 10.

In the section 10 (Fig. 7, *d*) and further to the east in the sections 11–13 (Fig. 7, *e*, 7, *f* and 8, *a*), where the coastal shelf is markedly narrowed, the main RC jet was located above the greater depths and in the whole was weakened. Closer to the shore the eastward current passed forming the coastal periphery of the anticyclonic cycle. It is well distinguished on the map of the horizontal distribution of current vectors (Fig. 3, *b*). Within this eastern current, two velocity cores were observed – an intense near-surface (up to 25–35 cm/s) and a weaker subsurface one (up to 10–15 cm/s) at depths of 50–75 m. In the section 11, the subsurface velocity core of the eastern stream shifted to the seaward part, while a weak westward stream (5–10 cm/s) was noted in the 25–75 m layer, indicating a cyclonic reversal of the currents at these depths (Fig. 7, *e*). It is possible that such a complex stream pattern in this area is associated with the RC jet running-in to the brow formed by the bottom topography about abeam the Cape Ayu-Dag.

In the eastern sections 14–18, which had a greater length towards the open sea, two RC jets were recorded again. The velocity core of the more intense northern branch was located in the upper 50 m layer. The velocity increased from 20 cm/s in the section 14 to 50–60 cm/s in the sections 16 and 17, and again decreased to 30 cm/s at the eastern boundary of the polygon (the section 18) (Fig. 8, *b – f*). Moving to the east from the section to the section, the northern RC branch shifted to the shelf. The seaward RC jet had relatively low velocities ~ 15–20 cm/s and weakened further eastward. In the sections 14 and 15, the velocity core along the 15 cm/c isotach was located in the upper 100 m layer, and in the section 16 along the 10 cm/s isotach in the layer 120–200 m. In the section 17, the southern branch was not traced, and at the extreme eastern section 18 was manifested again in the form of a relatively weak (up to 10 cm/s) flow in the 50-200 m layer.

Conclusions. Analysis of the water circulation peculiarities in the northern Black Sea based on the data of the surveys carried out in the 87th cruise of R/V Professor Vodyanitsky showed that the westward flows being the Rim Current manifestation are predominant within the studied water area.

In the western part of the polygon, the Rim Current was divided into three branches. The northern branch is located over the shelf, the central one – over the continental slope and formed the southern Sevastopol anticyclone (SA) periphery and the southern one – over the deep-sea regions. It was revealed that during the survey the SA had an extremely asymmetric vertical power with a poorly developed northern periphery above the shelf and a more intense southern periphery above the continental slope.

In the central part of the polygon the Rim Current intensifies, at that one intensive stream is traced. In the eastern part of the polygon two branches of the Rim Current are observed: the intensive northern one over the continental slope and the coastal shelf, and the one located closer to the deep-sea regions (its velocity is rather low and it weakens moving eastward). The seaward RC jet had a relatively low velocity, which decreased in the eastern direction, and the branch itself was deepened.

In the upper layer to the east off the Cape Ai-Todor, the anticyclonic gyre is observed; whereas within the 50–100 m below it, the cyclonic turn of the currents is revealed.

Comparison of the survey results with climatic data showed that the effect of the synoptic and interannual variability of the water circulation formed some differences from the climate circulation in the structure of the currents in July 2016. According to the measurements, several Rim Current branches were identified and a clearly expressed Sevastopol anticyclone, the anticyclone near the southeastern coast of the Crimea, a closed cyclonic gyre in the southeast of the polygon were recorded.

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