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MARINE PHYSICS

Synoptic Variability of Currents in the Coastal Waters of Sochi

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Abstract—We performed investigations of synoptic variability of bottom and surface currents, the flow rate of the Mzymta River, and the wind speed measured with high resolution (10 min periodicity) in the coastal zone of the city of Sochi in May 2009, 2010, 2011, and 2012. Based on the measurements, a Fourier spectral analysis and harmonic analysis were carried out for both low-frequency and high-frequency components of the variability of the current velocities and wind speed. The analysis revealed a similarity of the structures of the main oscillation periods for the currents in the low-frequency spectrum and significant fluctuation periods for the currents in the high-frequency range. In addition, we studied the internal waves generated by the river plume.

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1. INTRODUCTION

This article studies the synoptic variability of the currents in the area influenced by the runoff of the Mzymta River in the coastal zone of the Adler district of the city of Sochi. The main attention is paid to the variability on small temporal (starting from the first tens of minutes) and spatial (starting from hundreds of meters) scales.

The studies are based on high resolution velocity measurements of the bottom and surface currents, which were performed with a periodicity of 10 min. The measurements were made during four expeditions organized in 2009, 2010, 2011, and 2012. The studied area is located in the inner part of a shelf at the eastern extremity of the Russian sector of the Black Sea coast (Fig. 1). This narrow shelf, which width does not exceed several kilometers, is strongly influenced by the coastal runoff of the Mzymta River, one of the largest rivers of the Black Sea coast of Russia (the long-term mean annual discharge of the river is 1.56 km^3), as well as several small rivers (the Khosta, Kudepsta, and Kherota). The measurements were taken for 5–6 days at the same time every year (in the second half of May) during the spring flood.

In this paper, we describe the results of the analysis of the flow and wind speed data obtained in the expeditions of 2009–2012. This work can be regarded as a continuation and expansion of our article [1], which published the processing results of such measurements for 2009. By combining the data for all four years of observations, we turn to the study of the general variability patterns of the currents in the coastal area of Sochi and their possible connection with the variability of the wind. We also separately discuss internal waves possibly generated by unsteady motion of the river plume.

2. DATA INPUT

The measurements were performed at a site located in the coastal waters of the Adler district of Sochi between the estuaries of the Kudepsta and Mzymta rivers. In 2009, the measurements were taken from May 20 to May 27; in 2010, from May 26 to May 29; in 2011, from May 25 to May 30; and, in 2012, from May 16 to May 19. Thus, all four measurement periods corresponded to almost the same conditions of the seasonal cycle characterized by the spring warming of the upper layer of the sea and the river flood runoff.

During the fieldwork, the mooring stations were equipped with mechanical SeaHorse tilt current meters [13]. A SeaHorse Meter is a cylinder that has small positive buoyancy, one end of which is attached to an elastic cord at the bottom of the load and on the second (free end) a tilt sensor Hobo Pendant G Data Logger UA-004-64 is fixed. When there is no near-bottom current, the cylinder is positioned vertically. Under the influence of a current, the cylinder deviates from its vertical position and the sensor measures the angular displacement, on the basis of which, from the known calibration dependence, the velocity components of the near-bottom current are then calculated. The anchored stations were installed at 3 points in 2009 and 2012 and at 5 points in 2010 (Fig. 1).

During all the expeditions, all the measurements were taken at the points “Yug” (43.401° N, 39.941° E; depth 15 m; distance to the beach 200 m) and “Mzymta” (43.413° N, 39.922° E; depth 8 m; distance to the shore 200 m) located opposite to the mouth of the Mzymta River. The latter station, in addition to the SeaHorse tilt current meter, in 2009 and 2011 was also equipped with a Nortek Aquadopp acoustic current meter set at a depth of 2 m below the

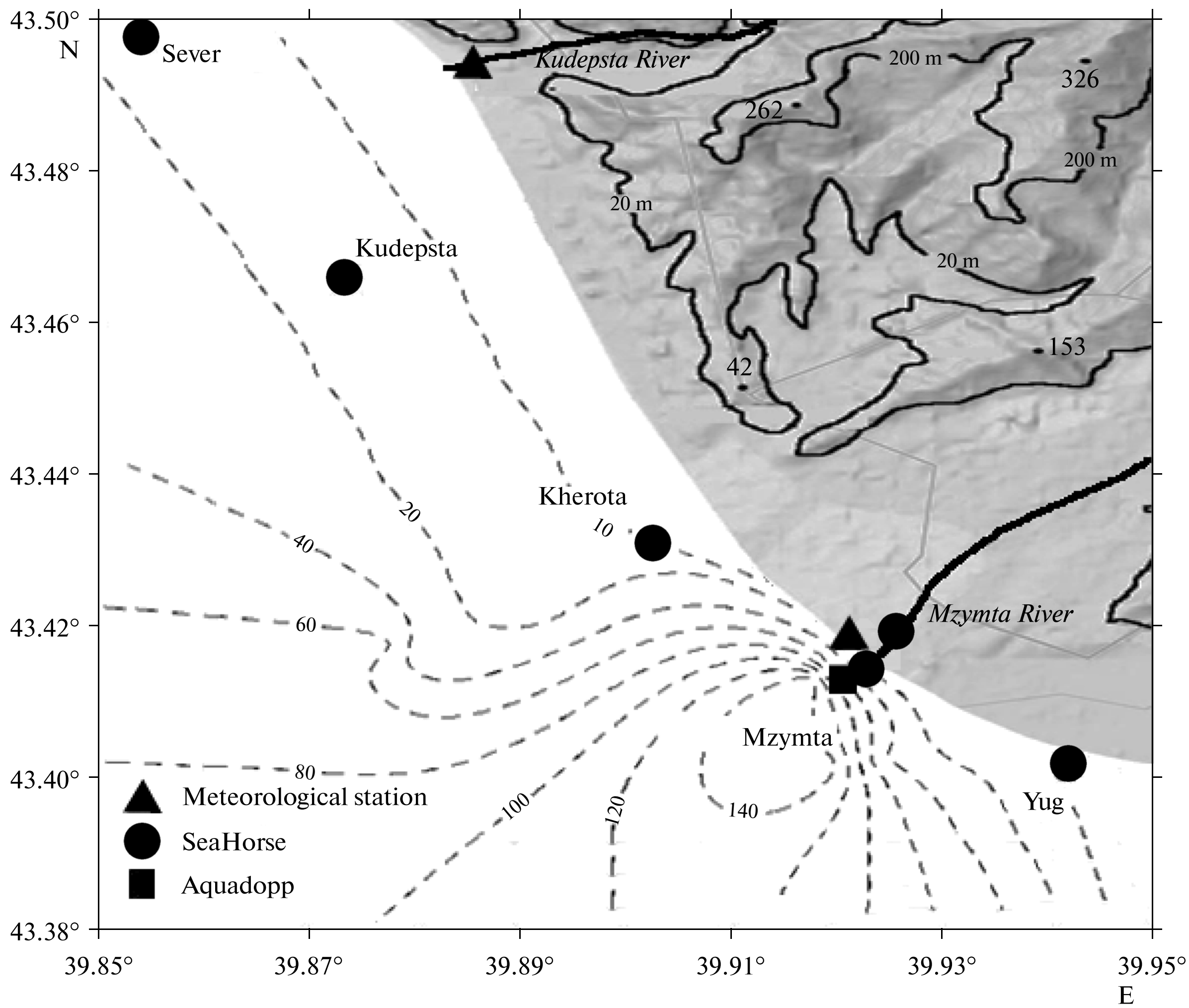

Fig. 1. Map of the studied region and location of the anchored and meteorological stations. The dashed lines in the sea show the isobath lines (m), and the solid lines on the shore designate the isogipsums of the elevation above the sea level (m).

surface of the sea. This device measures the Doppler frequency shift that occurs when sound propagates in a moving medium and, on the basis of this measure, calculates the velocity of the current. In 2009 and 2010, measurements were also taken by an anchored station "Sever" (north) (43.499° N, 39.855° E; depth 13 m; distance to the beach 1100 m) and, in 2010, 2011, and 2012, at the station "Kherota" (43.429° N, 39.906° E; depth 8 m; distance to the beach 500 m) near the estuary of the Kherota River. In 2010, the anchored station "Kudepsta" (43.463° N, 39.870° E; depth 14 m; distance to the beach 2000 m) was put in place (Fig. 1). In addition, during the field work in 2010–2012, in order to assess the runoff variability, measurements of the flow rate of the Mzymta River were made directly in the riverbed. For this purpose, a SeaHorse tilt current meter was installed at the river bottom at a depth of 1–1.5 m and at a distance of about 60–100 from its confluence with the sea. The current velocities at all the stations were recorded with discreteness of 10 minutes. At the same time and with the same time discreteness, measurements were made of the wind speed and direction. In 2009 and 2010, they were performed using two portable automatic meteorological stations installed on the seafront near the mouths of the rivers Kudepsta and Mzymta. The distance between them was 8 km. Estimates of the spatial inhomogeneities of the local wind fields, as well as their impact on the flow regime, obtained from these data are presented in the article [1]. In 2011 and 2012, we used a single meteorological station put in place at the mouth of the Mzymta River.

In this article, we separately consider the "low-frequency" and "high-frequency" variability of the currents and wind. Certainly, the boundary between these spectral intervals is conditional and can be defined arbitrarily. Here, by high-frequency (low-frequency), we understand changes with characteristic periods of less (greater) than 6 h.

Table 1. Periods (h) of fundamental harmonics of the low-frequency component along the coastal component of the current velocity over the measurement periods in 2009–2012

Year	Station					
	Mzymta bottom	Yug bottom	Sever bottom	Kherota bottom	Mzymta surface	Kudepsta bottom
2009	17.2	17.3	17.6	–	16.8	–
2010	18.4	25.1	17.6	23.3	–	22.0
2011	23.0	22.9	–	15.7	15.5	–
2012	17.2	16.5	–	20.8	–	–

3. ANALYSIS OF THE CURRENT MEASUREMENT DATA

3.1. Average and Maximum Values

As indicated above, the measurements of the currents in the near-surface layer were made during the expeditions of 2009 and 2011 at the station Mzymta. The recorded velocities of the surface currents were rather high, the maximum values reached 63 cm/s in 2009 and 48 cm/s in 2011, and the average velocity was 11 cm/s in 2009 and 8 cm/s in 2011.

The velocities of the near-bottom currents were monitored during the expeditions in 2009–2012 at five stations (an example of a series of velocity values for the near-bottom currents at the station Mzymta is shown in Fig. 2). The maximum velocity of the bottom current at the station Sever was 19 cm/s in 2009 and 29 cm/s in 2010 with the corresponding mean values of 6.0 cm/s in both cases. At the station Kudepsta (2010), the maximum velocity was 38 cm/s, and the mean velocity was 5.9 cm/s. For the station Kherota, the maximum observed values were 29 cm/s (2010), 29 cm/s (2011), and 26 cm/s (2012) with the corresponding mean values of 5.3 cm/s, 5.3 cm/s, and 5.6 cm/s. For the station Mzymta, the following maximum and mean velocity values were recorded: 24 cm/s and 6.6 cm/s in 2009, 24 cm/s and 3.7 cm/s in 2010, 31 cm/s and 13.7 cm/s in 2011, and 10 cm/s and 2.0 cm/s in 2012. Finally, for the station Yug, the analogous values were 22 cm/s and 6.7 cm/s in 2009, 41 cm/s and 8.0 cm/s in 2010, 44 cm/s and 5.0 cm/s in 2011, and 26 cm/s and 4.0 cm/s in 2012.

It is clearly seen that the maximum and mean values of the surface current velocity are in general considerably higher than the corresponding values for the near-bottom currents.

3.2. Low-Frequency Variability of the Current Velocity

As noted above, by a low-frequency component of a time series of data in this section and below, we understand the result of filtering the initial time series using a 6-hour moving average.

The fourier spectra were calculated for the selected on this basis low-frequency part of the variability along the coastal components of the surface and near-bottom currents over the measurement periods in 2009–2012 (Figs. 3–6). In the studied area, the orientation of the coastline practically coincides with the meridional direction (the deviation does not exceed 10°), so the meridional component of the velocity was taken as its alongshore component. All the obtained main fluctuation periods for 2009 and 2012 were in the range of 14–19 h. The inertial period for this latitude is 17.6 h.

For the more detailed analysis of the spectral structure of the low-frequency variability along the coastal components of the current velocity for each series, a harmonic function of the form $c(t) = A\sin(wt + \varphi)$ was selected that provided the least rms (standard) deviation from the specified time series. Periods $T = 2\pi/w$ of these fundamental harmonics for each series are presented below in Table 1.

All the obtained fundamental harmonics for the data series are clearly divided into two groups. The first group consists of functions with periods of oscillation close to 17.6 h, which indicates a relationship with inertial oscillations. The oscillation periods for the functions of the second group are close to 24 h, which can be due to the breeze component of the wind (see below).

3.3. High-Frequency Velocity Fluctuations of the Currents

We now turn to the study of the high-frequency variability in the near-surface and near-bottom currents. By the high-frequency component of a data series in this section and below, we understand the difference between the basic (initial) series and the low-frequency component found above.

As a result of the harmonic analysis performed in accordance with a procedure similar to that described

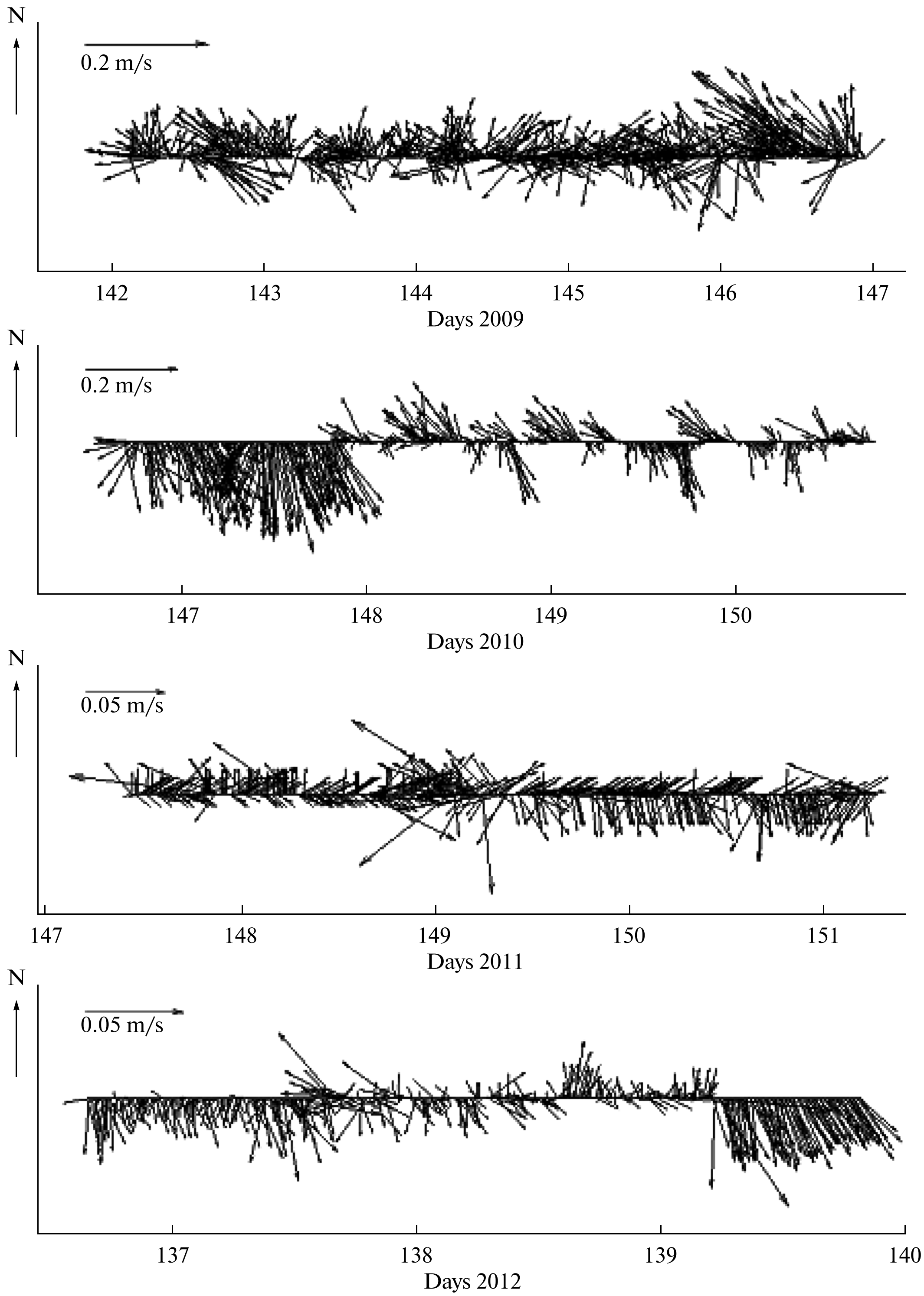

Fig. 2. Series of near-bottom current velocities measured at the station Mzymta over the measurement periods in May of 2009–2012.

above for the low-frequency fluctuations, we identified the main periods of high-frequency fluctuations of the alongshore components of the surface and near-bottom currents during the measurement periods (Table 2).

As is clear from Table 2, the periods of the fundamental harmonics of the high-frequency fluctuations in the alongshore velocity component of the near-bottom currents during the measurement period in 2009–

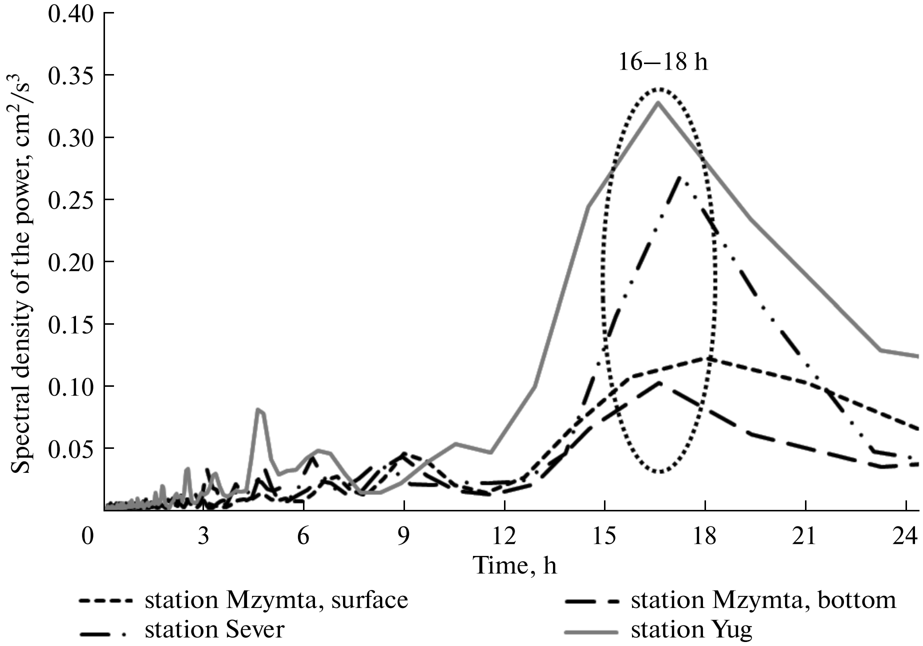

Fig. 3. Spectral structure of the low-frequency variability in the alongshore components of the surface current velocities at the station Mzymta and of the near-bottom current velocities at the stations Mzymta, Sever, and Yug during the measurement period in May of 2009. The dotted line separates the region of the highest frequency power.

2012 averaged 3.9 h and the velocities of the near-surface currents averaged 4.7 h.

4. ANALYSIS OF THE WIND MEASUREMENT DATA

4.1. Low-Frequency Fluctuations of the Wind Speed

The spectral analysis of the low-frequency component of the wind speed component transverse to the shore showed in all the cases the presence of the main period close to 24 h (22 to 27 h in different series, Figs. 7–8). We can assume that these periods are associated with the breeze variations of the wind speed. Similar periods of fundamental harmonics of the low-frequency variability along the coastal component of the current velocity over the measurement periods in 2009–2012 close to 24 h (see Section 3.2) can be attributed to the effect of the breeze variations.

The spectral analysis of the low-frequency variability of the alongshore component of the wind speed has not revealed any significant periods.

4.2. High-Frequency Fluctuations of the Wind Speed

The Fourier spectral analysis of the high-frequency component of the variability of the wind speed component transverse to the shore yielded periods of fundamental fluctuations that were equal to 4.0 and 4.6 h for the data of the meteorological station Kudepsta in 2009 and 2010, respectively (Fig. 9), and 4.5 and 4.2 h for the data of the meteorological station Mzymta in 2011 and 2012, respectively (Fig. 10). For the alongshore components, these values were 5.0 and 5.8 h for the station Kudepsta in 2009 and 2010, respectively, and 6.2 and 4.0 h for the station Mzymta in 2011 and 2012, respectively.

As in the case of the low-frequency variability, the spectral analysis of the high-frequency component of the alongshore component of the wind speed did not reveal any significant periods.

Therefore, the main period of high-frequency fluctuations of the layer wind speed over the observation period in 2009–2012 averaged 4.8 h. As noted above in Section 3.3, the same period was also characteristic of the high-frequency fluctuations of the alongshore velocity of the surface current at the station Mzymta. Thus, the high-frequency fluctuations in the near-surface currents may be due to the wind exposure. At the same time, no similar direct relationship between the wind exposure and the high-frequency fluctuations in the near-bottom currents has been detected. We drew a similar conclusion in our work [1] that investigated the correlation between the wind and the surface and near-bottom currents in this area. This result can be attributed to the fact that the station Mzymta during the measurements was located directly in the propagation area of the diluted (freshened) coastal runoff and, therefore, the near-surface currents were measured within the plume waters. According to some publications (see, for instance, [4]), the jump in the water density at the lower boundary of the plume prevents

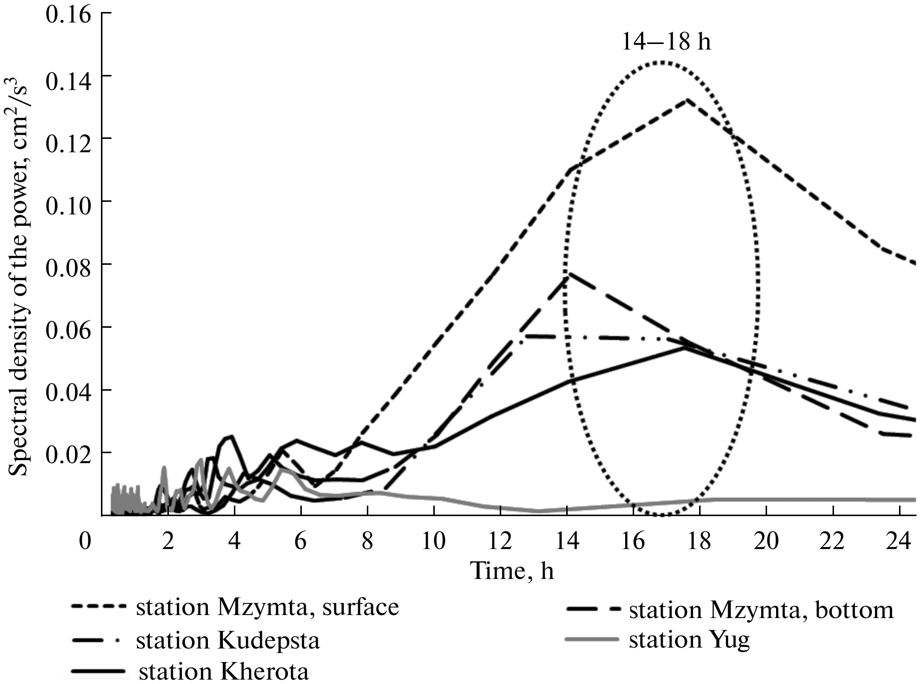

Fig. 4. Spectral structure of the low-frequency variability in the alongshore components of the surface current velocities at station Mzymta and of the near-bottom currents at the stations Mzymta, Kudepsta, Kherota, and Yug during the measurement period in May of 2010. The dotted line separates the region of the highest frequency power.

the transfer of wind momentum to the underlying marine waters.

5. ANALYSIS OF THE MEASUREMENT DATA FOR THE CURRENT VELOCITY OF THE RIVER MZYMTA

The current velocity of the Mzymta River was measured during fieldworks in 2010–2012. The maximum values of the current velocity of the river were 61 cm/s in 2010, 108 cm/s in 2011, and 103 cm/s in 2012 (Fig. 11). The fluctuations in the volume of the river runoff for the Mzymta River during the measurement time can be considered directly proportional to the fluctuations in the current velocity of the river because no significant change in the level of the river was observed over this short period.

The Fourier spectral analysis identified the main periods of low-frequency and high-frequency variability in the current velocity of the river (Fig. 12). The period of the fundamental harmonic for the low-frequency fluctuations was 24 h in 2010, 9 h in 2011, and 16 h in 2012, while the figures for the high-frequency fluctuations were 2.9 h in 2010, 3.6 h in 2011, and 3.9 h in 2012.

Thus, there is no evident connection between the spectral structure of either the low-frequency or high-frequency fluctuations in the power of the runoff of the

Table 2. Periods (h) of fundamental harmonics of the high-frequency component along the coastal component of the current velocity over the measurement periods in 2009–2012

Year	Station					
	Mzymta bottom	Yug bottom	Sever bottom	Kherota bottom	Mzymta surface	Kudepsta bottom
2009	3.2	4.8	4.5	–	4.9	–
2010	3.8	3.0	4.6	3.4	–	2.8
2011	3.0	3.9	–	3.2	4.5	–
2012	4.3	4.0	–	4.9	–	–

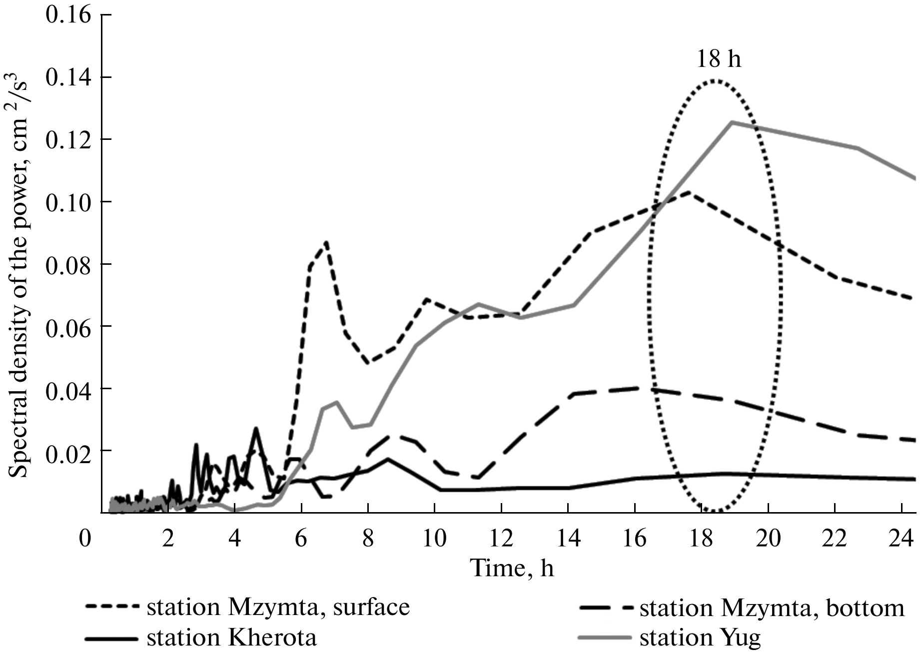

Fig. 5. Spectral structure of the low-frequency variability in the alongshore components of the surface current velocities at the station Mzymta and of the near-bottom currents at the stations Mzymta, Kherota, and Yug during the measurement period in May of 2011. The dotted line separates the region of the highest frequency power.

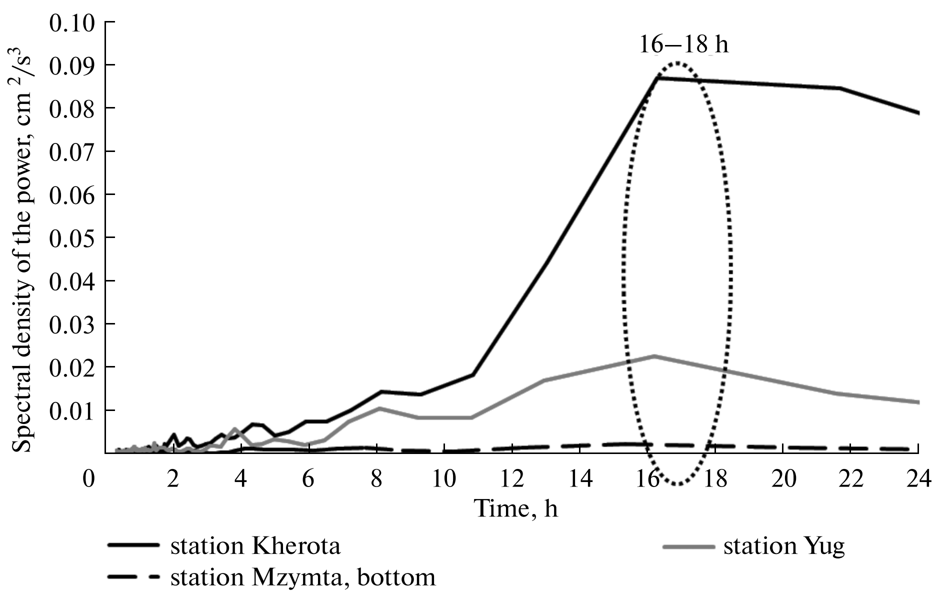

Fig. 6. Spectral structure of the low-frequency variability in the alongshore components of the near-bottom current velocities at the stations Mzymta, Kherota, and Yug during the measurement period in May of 2012. The dotted line separates the region of the highest frequency power.

Mzymta River over the measurement periods in 2010–2012 and the variability in the near-bottom and near-surface currents. The synoptic fluctuations in the runoff power of large rivers can significantly affect the dynamics of the surface currents in river plume areas [9]; however, no such connection was observed in our case.

6. INTERNAL WAVES GENERATED BY A PLUME

Internal waves in many cases are responsible for the most intensive high-frequency fluctuations in the velocity in ocean coastal areas [5, 10, 11]. The nonstationary motion of the river plume, as was shown in [3, 6, 8, 12], can generate internal waves that affect the

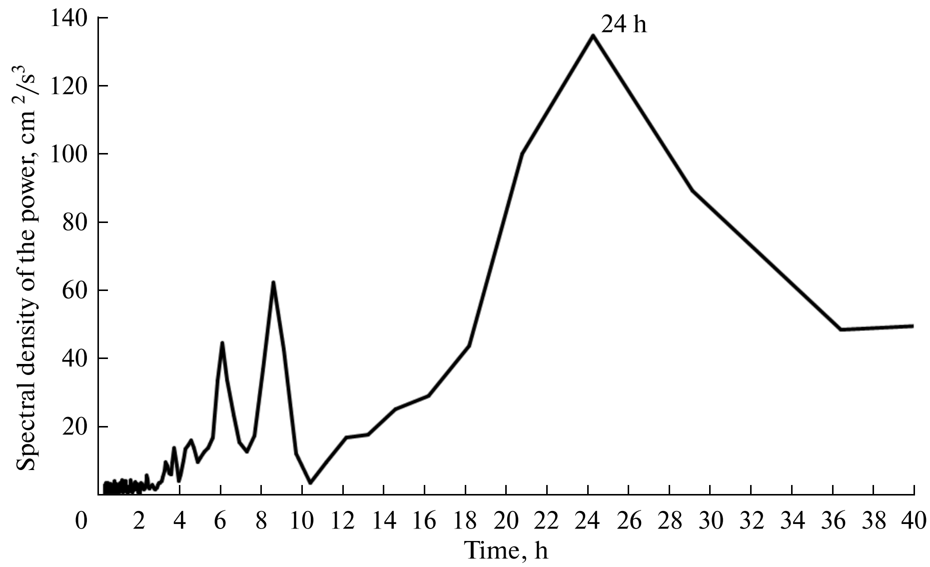

Fig. 7. Spectral structure of the low-frequency variability in the wind speed component transverse to the shore at the meteorological station Kudepsta during the measurement period in May of 2009.

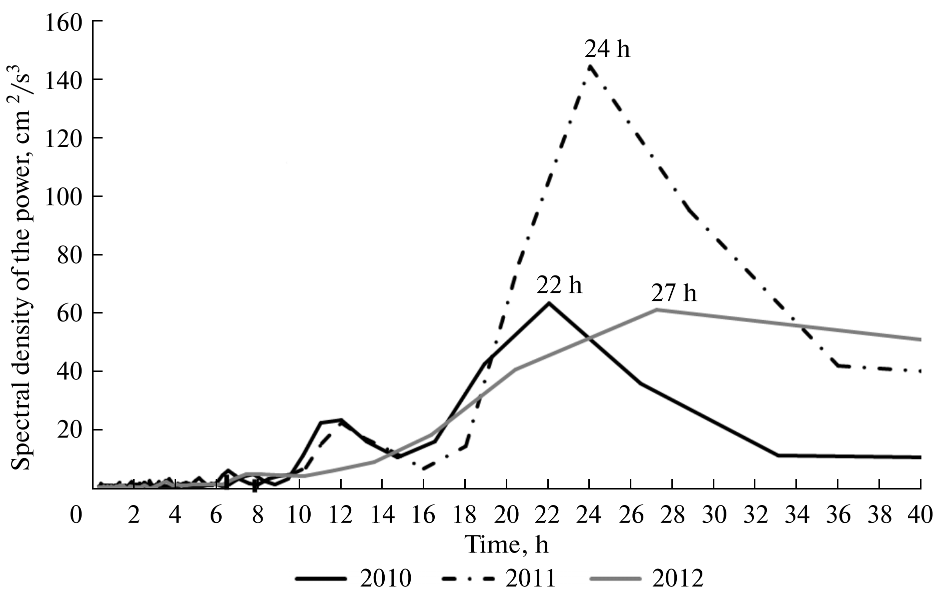

Fig. 8. Spectral structure of the low-frequency variability in the wind speed component transverse to the shore at the meteorological station Mzymta over the measurement periods in May of 2010–2012.

processes of turbulent mixing on the shelf [7, 14]. For the semi-enclosed Black Sea, in which there are practically no tides but which abounds in sources of freshwater runoff, the effect of which is an order of magnitude greater than the ocean average, such a mechanism for the generation of internal waves is potentially particularly important. In this section, on the basis of the measurement data, we present arguments for the existence of internal waves generated by the plume of the Mzymta River and estimate the values of their wave parameters.

Over all four periods of measurements in 2009–2012, the fundamental harmonics of the high-frequency velocity variability of the alongshore near-bottom currents at all the stations had close periods that averaged 3.9 h. This suggests that the high-frequency fluctuations observed in different years have a common nature. At the same time, no such periods were detected in connection with either the wind action or fluctuations in the runoff intensity of the Mzymta River (see Sections 4.3 and 5).

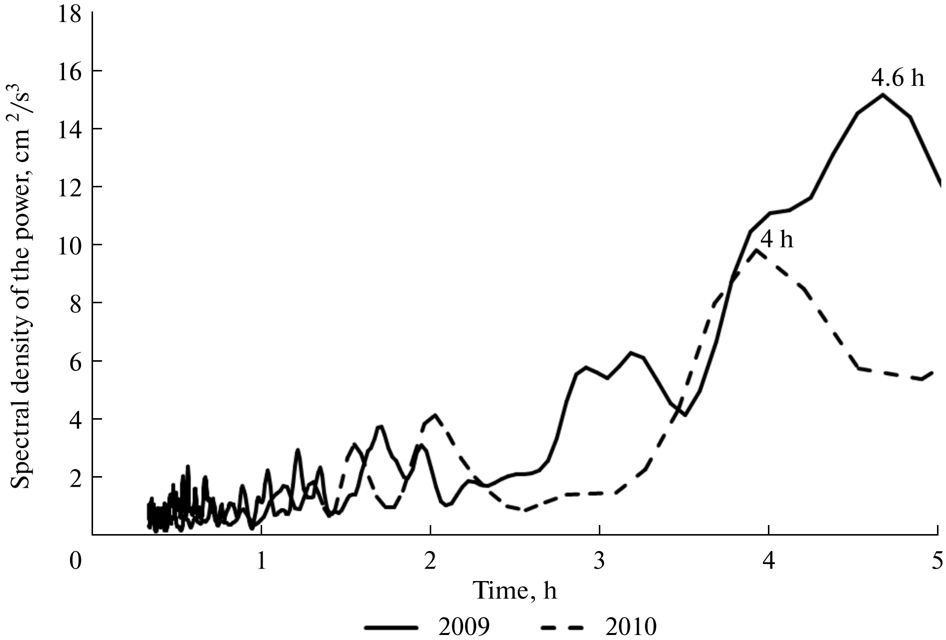

Fig. 9. Spectral structure of the high-frequency variability in the wind speed component transverse to the shore at the meteorological station Kudepsta over the measurement periods in May of 2009 and 2010.

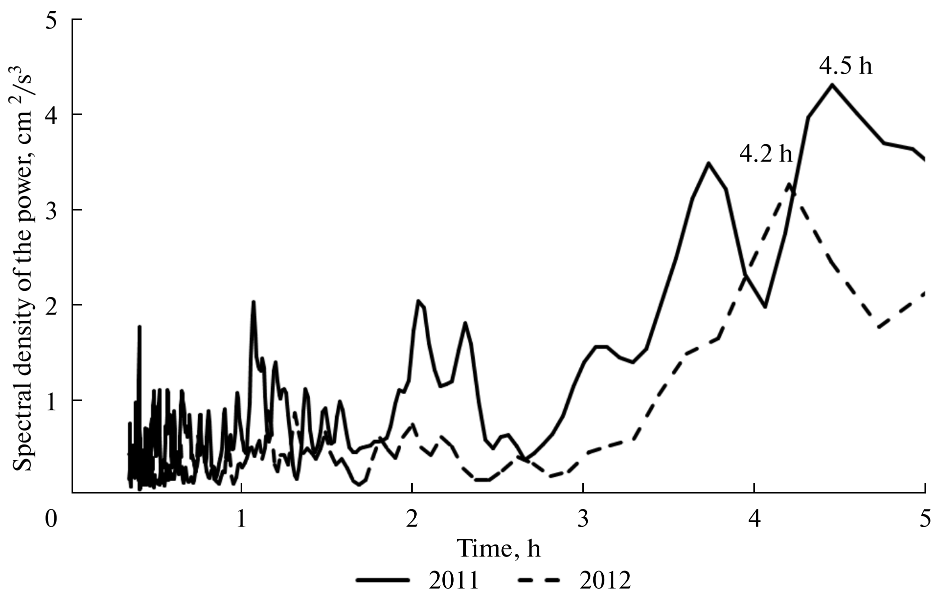

Fig. 10. Spectral structure of the high-frequency variability in the wind speed component transverse to the shore at the meteorological station Mzymta over the measurement periods in May of 2011–2012.

Let us hypothetically assume that the fluctuations in the current velocity with a period of about 4 h are caused by internal waves that propagate from a "quasi-point" source at the mouth of the Mzymta River. By identifying the corresponding harmonics in the series of velocity measurements at the station Mzymta located directly at the mouth and at the stations Sever, Yug, and Kherota located at known distances to the north and south of the mouth, we can obtain the relations between the phases of the fundamental harmonics at these points and then calculate the phase velocity of the internal wave propagation. This simple procedure yields the values summarized in Table 3. In the calculations of the phase velocities of the internal wave, it was decided to neglect the influence of the background current as the average values of the mea-

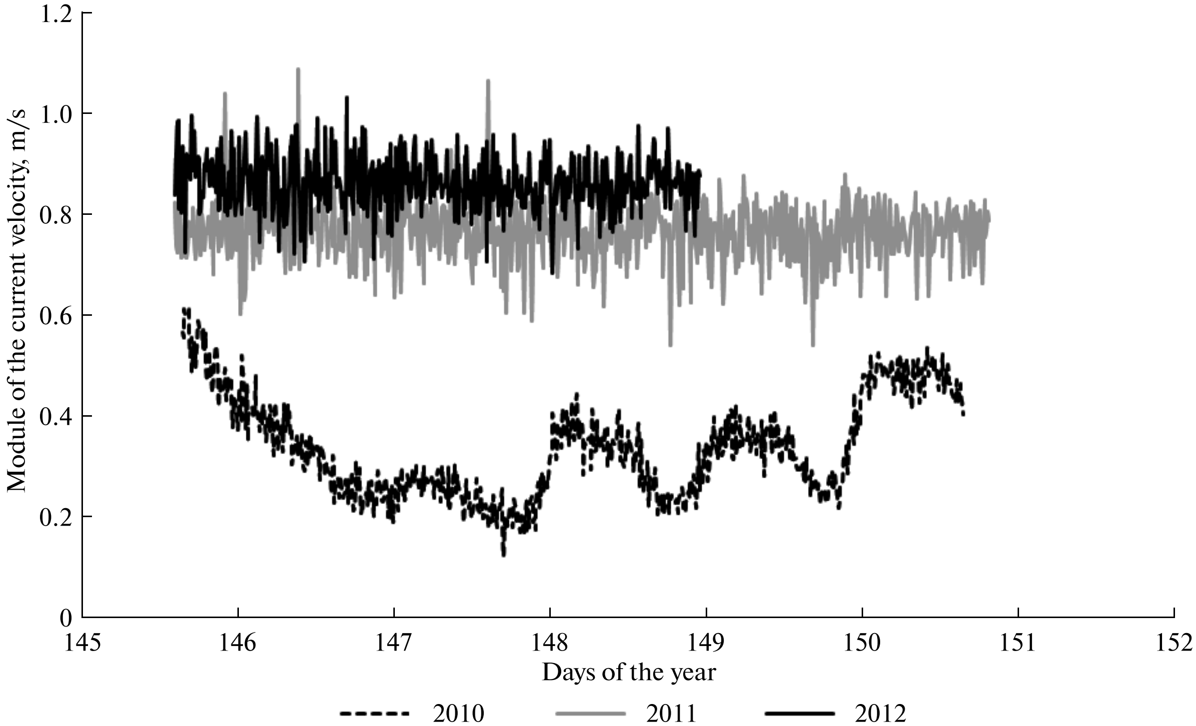

Fig. 11. Changes in the current velocity of the Mzymta River during the measurement period in May of 2010–2012.

sured velocities of the near-bottom currents were relatively small (see Section 3.1); approximately an order of magnitude less than the estimated propagation velocity of the internal wave.

If our initial hypothesis is correct and the pattern of the velocity variability at different points is described by the propagation of one and the same wave from a point (discrete) source, we can expect that the thus obtained phase velocities will coincide (or at least will be close to) with the values calculated for the intervals Mzymta–Sever, Mzymta–Yug, and Mzymta–Kherota; that the values calculated for the different years will be relatively close because the nature of the vertical stratification and the other oceanographic conditions were similar in all the cases; and that the calculated values will be comparable with those prescribed by approximate theoretical formulas, for example, for the case of two-layer stratification.

As can be seen from Table 3, the first two criteria in this case appear to be reasonably satisfied. In order to test the third condition, we can calculate the theoretical propagation velocity of an internal wave in a two-layer fluid. Since there is a water layer freshened by the river runoff in the upper part of the water column, the approximation of the vertical stratification by a two-layer model in our case appears to be physically justified (at least on a qualitative level). This velocity is given by the formula [2]

$$C = (g\,\Delta\rho/\rho h(H-h)/H)^{1/2},$$

where ρ is the sea water density, $\Delta\rho$ is the difference in the densities of the sea and river water, g is the gravitational acceleration, h is the depth of the density jump (the thickness of the plume), and H is the sea depth. By substituting the characteristic values, we see that the formula satisfactorily reproduces the values presented in Table 1.

Finally, we would like to offer another argument in favor of the proposed hypothesis. In addition to the oscillation of the current velocity field, internal waves are to cause periodic vertical displacements of isopycnals (and isohalines) in the surrounding sea. If the waves are really generated by the river plume, the depth of the corresponding isohalines as a function of the horizontal coordinates and time should be described by a traveling wave equation with a source in the estuary area. In order to test this assumption, we can use the available data of CTD soundings.

Thus, during the fieldwork of 2011, for four consecutive days from May 27 to May 30, we daily performed 6–7 soundings of the temperature, salinity, and density from the surface to the bottom at various points of the polygon. For every measurement, we determined the depth h of the 17 PSU isohaline. For reference, we could have also selected any other “reasonable” isohaline; however, it is the 17 PSU isohaline that roughly corresponds to the boundary between the desalinated water of the river plume and the surrounding marine waters. In each case, we also know the measurement time t and the distance x from the mea-

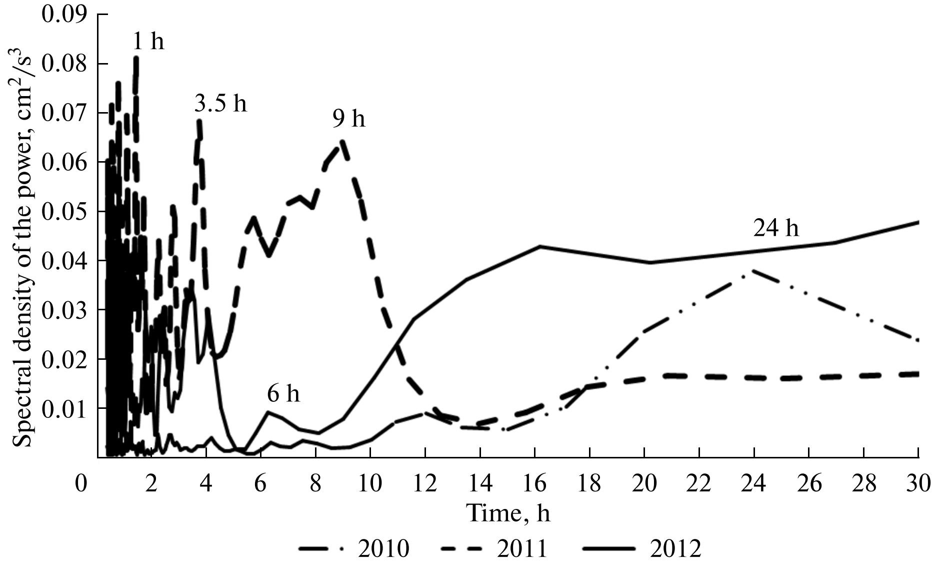

Fig. 12. Spectral structure of the variability in the current velocity of the Mzymta River during the measurement period in May of 2010–2012.

surement point to the estuary of the Mzymta River. Next, for each of these four separate days, the parameters were found (the amplitude A and the initial phase φ) of a wave of the given period of 3.9 h propagating from a point source localized at the mouth of the Mzymta River providing the least standard deviation at the points (x, t) from the measured occurrence depths h (Table 4). As can be seen, we observe a coincidence of amplitudes for all four wave functions obtained using this technique ($A = 0.4$ m). The average values of h_0 appeared to be close to each other (from 4.1 to 4.7 m), and the rms deviations δ assumed values in the range from 0.4 to 1.2 m.

Thus, we can say that, on each of the four consecutive days of measurements, the observed vertical displacements of the isohaline of 17 PSU with sufficient accuracy correspond to the propagation of internal waves with a period of 3.9 h from a source located near the mouth of the Mzymta River.

Data for all four days were also represented as a single series, and for it we also found the following matching traveling wave equation with a source in the vicinity of the river estuary that minimized the deviation of the value $h(x, t)$ from these measurement data:

$$h(x, t) = h_0 + A\cos(\varphi + w(t - x/v)),$$

where $A = 0.4$ m is the amplitude, $\varphi = 3.08$ rad is the initial phase, $w = 4.52 \times 10^{-4}$ s^{-1} is the angular frequency, and $v = 0.78$ m/s is the wave propagation velocity.

The standard (rms) deviation from the observational data for this wave was 0.92 m.

The above results must be seen as a strong (albeit indirect) argument in favor of the hypothesis about the existence of internal waves generated by the plume of the Mzymta River.

7. CONCLUSIONS

The synoptic variability of the currents in the area influenced by the runoff of the Mzymta River was studied on the basis of field measurements performed in 2009–2012 in the coastal zone of the Black Sea in the Adler district of Sochi. The low-frequency variability (understood here as variability with periods exceeding 6 h) of the currents in the shelf zone shows similar structure structures for the surface and near-bottom currents; in both cases, the low-frequency variability of the currents is primarily influenced by the inertial oscillations (with a period of 17.6 h) and the daily wind breeze circulation (with a period of 24 h). In the high-frequency variability of the currents in the surface layer, the prevailing oscillations are characterized by periods of 4.5–4.9 h. Similar periods are observed for the variability of the wind speed in this region; therefore, it can be assumed that the high-frequency variability of the surface currents is primarily determined by the effect of the wind. However, this is

Table 3. Phase velocity of the internal wave (m/s) calculated for various segments of the polygon

Year	Mzymta–Sever	Mzymta–Yug	Mzymta–Kherota
2009	0.78	0.75	–
2010	0.97	0.88	–
2011	–	0.80	0.64
2012	–	0.75	0.66

Table 4. Parameters of the wave functions with the smallest standard (rms) deviation from the internal wave generated by the plume for the corresponding observation periods in 2011

Date	A, m	φ, rad	h_0, m	δ, m
May 5, 2011	0.4	1.31	4.7	0.48
May 28, 2011	0.4	5.3	5.0	1.19
May 29, 2011	0.4	3.42	4.1	0.67
May 30, 2011	0.4	2.27	4.6	0.44
May 27–30, 2011	0.4	3.08	4.6	0.92

not the case for the near-bottom currents. The predominant frequencies of their short-period variability are generally higher than for the surface currents; they correspond to periods from 2.8 to 4.9 h (on average, 3.9 h). No connection has been detected between the variability of the near-bottom currents and the wind variability, which is consistent with the results of our earlier work [1]. The velocity oscillations of the near-bottom currents in this region can possibly be caused by the internal waves generated by the movement of the Mzymta River plume. The available data on the velocity measurements and profilings of the coastal thermohaline structure indirectly confirm this hypothesis. Its final verification, however, would require measurements with higher spatial resolution along the horizontal coordinates.

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