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# SEICHE DYNAMICS IN THE AZOV SEA CURRENT SYSTEM

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**Abstract:** The paper presents new results of an investigations of the cyclic currents of the Azov Sea. Using offshore and onshore surveys at buoy ADCP-stations the separation of the characteristic features of water transport in different areas of the Taganrog Bay was shown. Expeditionary observations showed that despite of the drift-gradient nature, the resulting current has the direction of the Don runoff current. Direct coastal measurements showed that the runoff current significantly predominates on the spits of the southern coast of Taganrog Bay. Seiche pulsations manifest themselves as a two to three-hour slowdown of the main flow at diurnal intervals. The division of the areas of the Taganrog Bay according to the trajectories of water movement is noticeable. The eastern part has a predominantly river regime of water circulation. In the central part the meridional component of seiche currents plays an important role in water mixing. The marine regime of water mixing prevails in the western part of the Taganrog bay. Test calculations show that the classical tidal analysis program T_TIDE is applicable with caution for the Sea of Azov. The visually observed diurnal and semi-diurnal sea level rises represent a superposition of waves of different natures. The results of the work correspond to the known patterns of energy exchange between the atmosphere and the ocean. Even weak winds lead to the development of wave processes at eigen frequencies close to tidal ones. Increasing winds contribute to the intensification of wave fluctuations and significant transfer of water during strong surges.

**Keywords:** the Azov Sea, the Taganrog Bay, tideless basins, seiches, positive and negative water setups, ADCP-measurements, lithodynamics, sea currents.

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RESEARCH ARTICLE

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## 1. Introduction

The Azov Sea is the most remote inland sea in Eurasia. It is maximally isolated from the Atlantic Ocean, the basin of which it is part of. Tidal phenomena in their traditional form are indistinguishable here. Level fluctuations are caused primarily by the forcing effect of the wind field. As a result of the interference of the oncoming surge waves and the reflected surge waves, standing waves are formed – seiches. Under the influence of the Earth's rotation, they are strongly deformed and form a system of seiche currents and level fluctuations – an amphidromic region [*Zhukov*, 1976]. Seiche amphidromic systems are manifested both in cyclic changes in sea level and in current directions [*Matishov and Grigorenko*, 2023]. The eigen frequencies of the basin's oscillations are close to tidal ones. Numerous experimental observations show an obvious cyclicity of the diurnal and semi-diurnal periods, which can be explained primarily by meteorological factors [*Kurchatov*, 1925].

It is known that diurnal and semi-diurnal level maximum consist of many single components, which are formed due to different mechanisms. High-resolution spectral analysis shows significant influence of radiative tides in the tidal frequency range. It is believed that radiation tides in the Sea of Azov are formed under the influence of breeze circulation [*Korzhenovskaia et al.*, 2022]. However, the regularity of harmonics characteristic of tides is disrupted by the action of wind. Similar water level dynamics are observed in other water bodies, for example, large lakes [*Ivanov et al.*, 2019]. How closely are the seiches of the Sea of Azov related to the tides? The work also sets the task of separating cyclical fluctuations in sea level (seiches) from forced ones (surges), and thus calculating the magnitude of surges without the influence of seiches.

## 2. Materials and methods

The work is based on the results of the Southern Scientific Centre of the Russian Academy of Sciences expeditionary investigations. Researches in the Azov Sea was carried out using a Doppler current meter Aanderaa RCM 9 LW. The frequency of the instrument's acoustic signal is 2 MHz, which allows the high-precision measurements at shallow depths. The discreteness of recording environmental parameters is adjusted by the operator from 30 s to 2 hours. During this period of time, the recorder sends 600 pings and makes one record of an average measurement with a quality mark. The current meter is additionally equipped with temperature, salinity and pressure sensors. Measurement data with a period of 30 min wer used in the work.

Measurements were carried out on board the R/V Deneb in May 2018 (one station) and December 2021 (five observation stations) Coastal survey data were used on the spits of the southern coast of Taganrog Bay – Chumburskaya and Sazalnitskaya in May and August 2023, respectively. Totally, the results of the current parameters measurements at eight stations in the Taganrog Bay of the Azov Sea were used to analyze water transport

Data from coastal water-level meters in the cities Temryuk, Yeisk and Donskoy village for 2021 were used to calculate seiche parameters. The estimation of seiches part in the amplitude of surge level fluctuations was assessed using the classical harmonic analysis package T_TIDE, implemented in the Matlab environment [*Pawlowicz et al.*, 2002]. A set of algorithms collected in the package allows to analyze data for periods up to a year, taking into account specific tidal components using nodal corrections within established confidence intervals. The list of tidal components includes 45 astronomical and 101 shallow water components. In the general case, an automatic selection of the closest component algorithm is used. It is possible to manually set the most characteristic oscillation period. The isolation and relatively small size of the Azov Sea lead to the formation of oscillatory systems at different frequencies for different areas of the sea and their mixing. This specificity forces us to use the most general settings of the T_TIDE package without specifying specific frequencies of water level oscillations. For the calculations, data of the water level during a strong negative water setup (06.10.2015 – 06.11.2015) and positive water setup (01.12.2021 to 31.12.2021) were used. Changes in water level in the Don Delta are compared with the seaward part of the Taganrog Bay, which is not directly influenced by the Don runoff (Yeisk from May 1 to June 30, 2021). Algorithms of the T_TIDE package constructed a spectrum of water level fluctuations in the village of Donskoy and the city of Temryuk, taking into account and without taking into account cyclic changes.

## 3. Results and discussion

Previous studies have revealed in detail the role of seiches in the Azov Sea [*Matishov and Grigorenko*, 2023]. Basing on long-term databases of expeditions and coastal water-level meters, it is shown that this is a widespread, regime-forming phenomenon. There is also given an estimation that the direction of the current will change in 12 to 24 hours, regardless of the wind field. The most typical vector-progressive diagrams of currents (Figure 1), constructed according the expeditionary data of the R/V Deneb, show that despite of the drift-gradient nature, the resulting current has the direction of the Don runoff current.

It was expected during planning the research that in the distal parts of the spits a cyclic alternation of the direction and speed of currents should be observed [*Matishov et al.*,

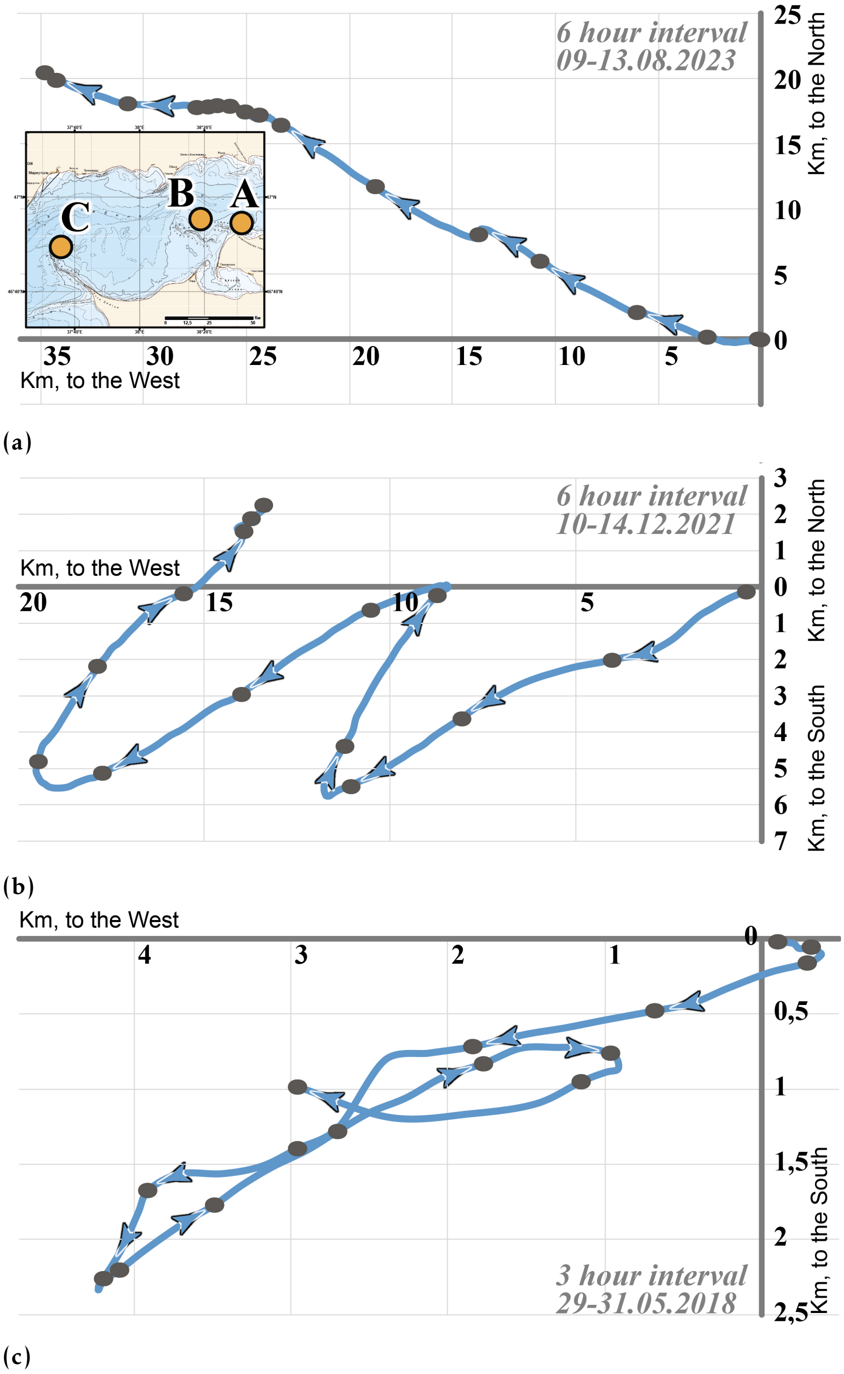



**Figure 1.** Vector-progressive diagrams of currents off the coast of the Sazalnitskaya Spit (a), in the seaward part of the Taganrog Bay (b) and in the seaward part of the Taganrog Bay near the Dolgaya Spit (c).

2022]. Direct measurements for a few days showed that the runoff current significantly predominates on the spits of the southern coast of Taganrog Bay (Figure 1a). Seiche pulsations manifest themselves as a two to three-hour slowdown of the main flow at diurnal intervals. The direction at this time changes to the opposite. This change is accompanied by minimal speeds, up to 10 cm/s. The establishment of a runoff current has the character of a breaking wave with a steep front slope close to collapse. During this phase, maximum velocities were measured – up to 60 cm/s on the Chumburskaya and Sazalnitskaya spits. After this, the speed levels out within 20–40 cm/s. The total movement of a water particle in a week under such conditions will reach 40 km.

In the central part of the Taganrog Bay, the meridional component of wave currents is noticeable (Figure 1b). The measurement under discussion was carried out during a strong three-day easterly wind, typical for the Azov region in winter. We will note that under the conditions of the strongest, during measurements, eastern wind (15–17 m/s), a northeastern current with a velocity of up to 25 cm/s was recorded. The maximum spatial transfer reached 20 km. However, the resulting movement of a water particle was reduced to 14 km, because the completion of measurements coincided with the compensatory stage of oscillations in the Azov Sea. In a week the transfer would be approximately 40 km.

The trajectory of water movement in the area of the Dolgaya Spit has a different appearance (Figure 1c). The measurements from the vessel were carried out at a distance approximately 15 km from the coast in almost calm conditions. The transfer was recorded strictly in the plane of the axis of the Dolzhansky Strait with a approximately diurnal period (21 hours). The range of fluctuations from east to west is relatively small, less than 5 km (about 35 km per week). We will note that the measurements were carried out for only a day, whereas in the cases described in Figures 1a and 1b – more than 3 days. All water exchange between the Taganrog Bay and the Sea of Azov itself occurs in the narrow strait between the Dolgaya and Belosarayskaya spits (Dolzhansky Strait). If we consider the long ridge of the underwater tip of the Dolgaya Spit, the width of the channel is only 20 km, while 30 km to the east the Taganrog Bay expands to 50 km. The narrowness helps to increase the currents. Even in calm conditions, a maximum speed 34 cm/s was noted. The average velocity of water movement of the entire Taganrog Bay in different areas to the west – the drainage direction of the Don, obtained from the results of measurements, is thus approximately 6 cm/s.

Let us consider the general scheme of water movement in the Taganrog Bay, constructed according to the results of current investigations at buoy stations since 2018 (Figure 2). For clarity, the movement of water particles is superimposed on a map of the Azov Sea bathymetry in the same scale. A vector-progressive diagram shows the distance and direction of movement of water particles at each time of measurement. Overlay on the map shows where a particle of water could move if there were no currents in the rest of the Taganrog Bay.

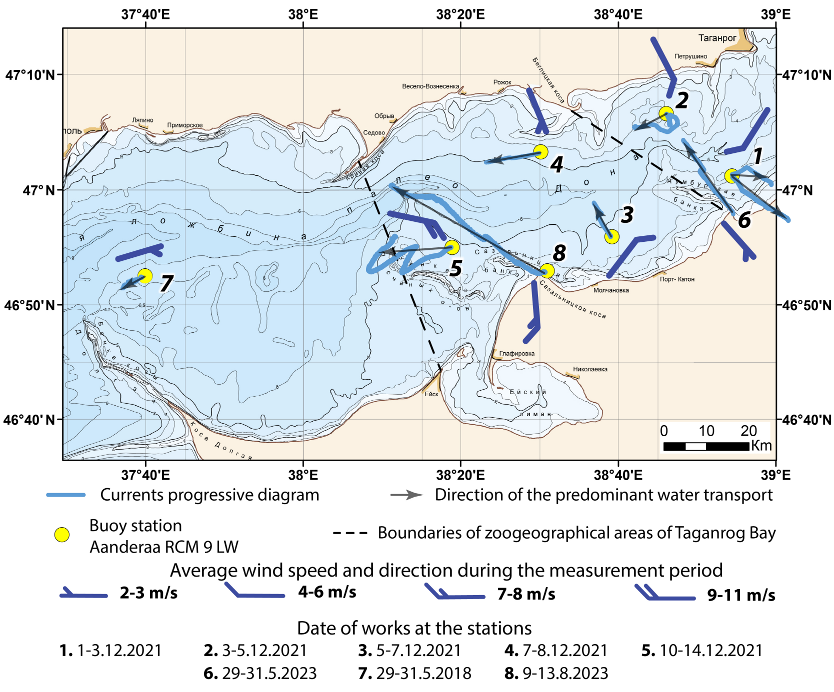



**Figure 2.** Vector-progressive diagrams of Taganrog Bay currents superimposed on a bathymetric map.

The division of the areas of the Taganrog Bay according to the trajectories of water movement is noticeable. The types of fluctuations are consistent with the known zoogeographical regions of the Taganrog Bay [*Gershanovich et al.*, 1991]. From the mouth of the Don to the cross-section of the Petrushinskaya spit – Chumburskaya bank, a predominantly river regime of water circulation operates. Salinity maximum during the absence of extreme surges do not exceed 5–7 p.s.u. The Don runoff current dominates in the water area; seiche transport is expressed in the periodic weakening of the runoff current. Movement of fresh current stream is possible from the southern to the northern shore. The biotic regime is close to the river one. The western border of the central region of Taganrog Bay is the cross-section between the Krivaya and Sazalnitskaya spits. Seiche currents of the meridional direction play an important role in water mixing. The central region is characterized by an average long-term location of the zoogeographic barrier for the habitat of freshwater fauna (5–7 p.s.u.). The western circulation volume of the Taganrog Bay is formed by the shallow ends of the Dolgaya and Belosarayskaya spits. The marine regime of water mixing prevails here. On the spectrum of level and salinity fluctuations, a pronounced 38-hour period of the 1-node seiche of the Sea of Azov is added [*Matishov and Inzhebeikin*, 2009]. Accordingly, the water area is characterized by sea salinity (more than 14 p.s.u. in modern times) and a corresponding distribution of bottom fauna. Due to the low water level of the Don, the runoff current in the Taganrog Bay has weakened. It is logical to correct the boundaries of zoogeographical regions to the east.

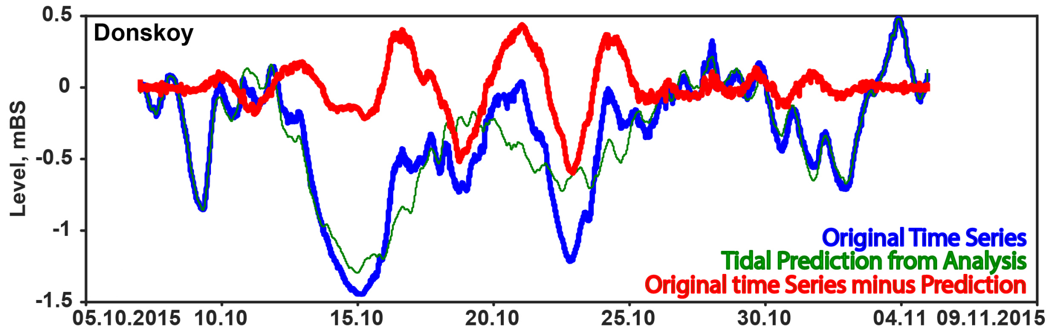
In direct form, the tides in the Azov Sea are weakly expressed. Researchers note a maximum theoretical value of up to 19.5 cm at the top of Taganrog Bay [*Korzhenovskaia et al.*, 2022]. Water-level meters show that the daily amplitudes of fluctuations in Yeysk and Donskoy sometimes exceed 1 m. Signal processing at specific periods is significantly difficult due to the mixing of different factors influencing on the level of the Azov Sea. A change in wind often leads to a change in the time of the characteristic onset of maximum and minimum levels. Using classical methods of harmonic analysis, an assessment of the interaction of radiation tides, seiches and surge water transport in the system of level fluctuations in the Sea of Azov was obtained (Figure 3).

The reasons and conditions for the formation of extreme surges are discussed in detail in [*Matishov and Grigorenko*, 2017]. The initial observation period, October 6–10, 2015 (Figure 1a), was accompanied by a drop in level to one m and had a strict daily cycle. The weakening of the surge wind was accompanied by the restoration of the shape of the level surface and three daily peaks of up to 0.2 m. The minimum phase of the surge was reached on October 15 with a drop in level of 1.5 m. Moreover, without taking into account cyclic fluctuations, the drop in level should have been only 0.2–0.25 m. The actual increase in water level to the initial level occurred from October 15 to October 20. At 20:00 on October 21, the second minimum level was reached – less than 1.2 mBS. The level recovered at 5:20 on October 23. Over the next four days, the level maximums gradually increased at daily intervals until they reached 0.3 mBS at 1:20 on October 27. With a regular daily period, the water surface decreased until 22:00 on October 31. Then, it sharply rose by 22:00 on November 2, 2015 to 0.5 mBS. The next minimum was recorded at 17:20 on November 3.

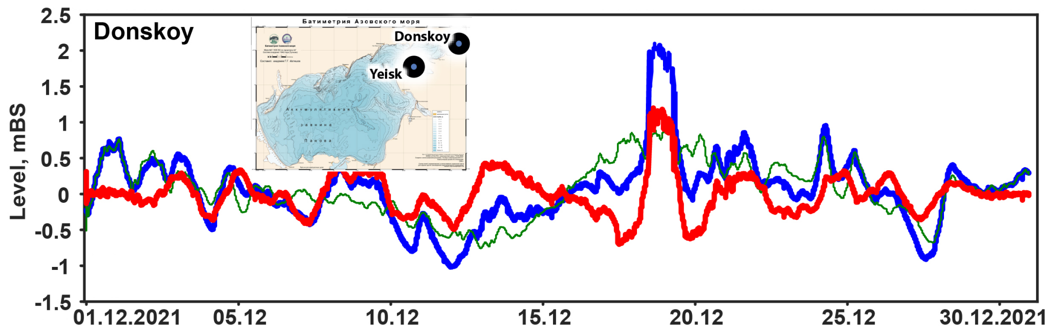
The absence of daily harmonics would lead to the formation of three surge maxima (up to 0.5 mBS) and minima (up to −0.5 MBS) of the level with an interval of 3–4 days. Changes in water level without taking into account wave dynamics would not lead to extreme surges.

Diurnal dynamics significantly influence the course of water levels in the east of Taganrog Bay during surges (Figure 1b). A cyclic series of small (up to 0.7 m) surges from the first to the fourth of December 2021 had a strict diurnal frequency. The maximum was reached around two o'clock in the morning, the minimum – around 14:00 – 15:00 daily.

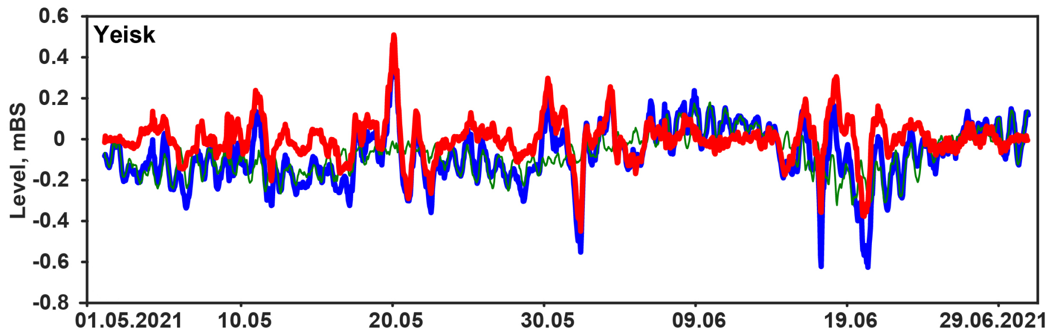
The subsequent difference between adjacent maxima lasted 40 hours. The amplitude reached 1 m. Until December 10, a pronounced diurnal variation was not observed. In the spectra of level fluctuations in the Sea of Azov (Figure 4a and 4b) there is a peak with a period of about 13–14 days. Apparently, it corresponds to the characteristics of the




(a)




(b)



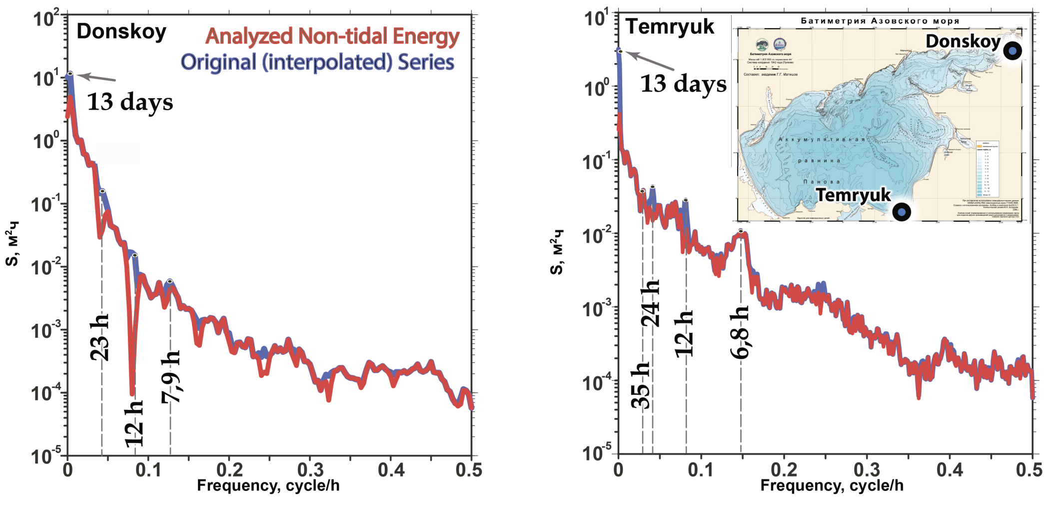

(c)

**Figure 3.** Results of processing data of water level in the Azov Sea using harmonic analysis methods. a) period of heavy wind negative water setup 10/06/2015 – 11/06/2015 in the Don delta; b) a period containing both daily fluctuations and a positive water setup more than 2 m from 12/01/2021 to 12/31/2021 in the Don delta; c) area of the Taganrog Bay, not directly influenced by the Don runoff (water-level meter in Yeisk) from 01.05 to 30.06.2021.

cyclonic circulation of the atmosphere in the Azov region. All extreme negative setups were recorded during two-week phases of decreasing levels. There are positive water setups, respectively, during long-term semi-monthly maximums. An example of such level dynamics is shown in Figure 3b and 3c. In particular, Figure 3b shows a negative water setup about 1 m on December 13th. After which the positive water setup wind phase began with a peak of water level at 14:50 on December 19 of 2.3 mBS. The diurnal periodicity of the oscillations appeared on December 25 during the phase of level decline during the two-week oscillation. Against the background of two-week fluctuations, the diurnal periodicity is not clearly expressed. At the same time, it is shown that the negative water setup on December 28 and the positive water setups on December 25 and 26 occurred because of a wave nature, without taking into account which the range of fluctuations would not have been 2 m, but about 0.5 m. The long-term stay of high waters on December 19 after filtering the semi-monthly periodicals would lead to an increase in the level up to half a meter higher relative to the actual one on December 14 and a decrease in the positive water setup on the 19th by more than 1 m.

The water-level meter in Yeisk is not directly influenced by the variability of the Don runoff. At the same time, Figure 3b shows both long-term cycles of increase and decrease in the level of the Taganrog Bay with a duration of about two weeks, and daily waves, well smoothed by software methods. The amplitude is significantly smaller compared to the Don delta. A number of positive and negative water setups were identified that did not have a distinct daily periodicity. At 2:00 on May 20, with a level of 0.4 mBS, at 6:00 on May 30 and a level of 0.2 mBS, at 9:00 on June 3, with a level of 0.3 mBS. Over the next 12 days, the daily amplitude of about 0.2 m is smoothed out. Fluctuations from June 14 to June 24 had approximately daily periods, but were mixed due to a general two-week decrease in water levels.

The spectra of surface level fluctuations were constructed for the Donskoy (Figure 4a) and Temryuk (Figure 4b) points, located on the opposite borders of the Sea of Azov. Similar patterns are observed in diurnal and semi-diurnal periods. The elongated shape of the Taganrog Bay contributes to an increase in wave energy, which is proven by deep decreases in the density of the filtered spectral signal relative to the original one at tidal periods. Both observation stations are also characterized by a two-week cycle of level oscillations. The nature of level changes in Temryuk is distinguished by small daily amplitudes, only 20–40 cm. The highest positive water setup in 2021 reached the level of 1.1 mBS (12/01/2021), and the negative water setup −0.6 mBS (10/06/2021), i. e. e. the total level difference throughout the year did not exceed 1.7 m. The Azov Sea in Temryuk is characterized by a 7-hour period of level fluctuations. This period is poorly recognized by the T_TIDE package, because it differs from the nearest tidal component (M4, with a period of 6.21 hours). The wide peak at this frequency is a local seiche of the Temryuk Gulf or a four-node seiche of the Azov Sea, the estimated period of which is 8.8 hours [*Matishov and Inzhebeikin*, 2009]. The maximum of the spectral signal at a frequency close to the period of a single-node seiche corresponds to a period of 35 hours. This value is also far from the nearest tidal ones, so the peak is lost in the spectrum, relative to the daily one.




**(a)** **(b)**

**Figure 4.** a) spectrum of level fluctuations in the village of Donskoy, taking into account and without taking into account cyclical fluctuations in water level in 2021; b) spectrum of level fluctuations in the city of Temryuk, taking into account and without taking into account cyclical fluctuations in water level in 2021.

## 4. Conclusions

The paper presents new results of an investigations of currents in the Azov Sea. It has been shown that water transport characteristics are very different in different areas of the sea. The dominance of runoff transport, despite of the pronounced wave nature of the current field, complements the estuarine characteristics of the Taganrog Bay. According to measurements (Figure 1 and 2), the eastern transport is observed in the areas of greatest depths of the bay and weakens towards the shores. Near the northern [*Matishov et al.*, 2022] and southern coasts, at near-zero levels and during negative water setups, the western current dominates. The current regime corresponds to the generally accepted zoogeographical zoning of the Taganrog Bay. The depth of location and height of accumulative sediments in the Azov Sea spit system depends on the maximum water level. For example, underwater banks (Sand Islands of the Sazalnitskaya Spit) with an upper edge at a depth of about 1 m are formed by a flow at a water level not lower than the normal one. Numerous shallows at the ends of the spits in the near-surface layer line up at near-zero water levels. Thus, the shallows of the underwater ends of the spits are stressed by the daily effects of seiche oscillations. Positive water setups of 2 m or more occur during extreme winds of the westerly component and are accompanied by high current speeds. The energy of one powerful surge is enough to significantly change the shape of the coastal topography of spits and islands.

This means that basing on the shape and age of accumulative bodies, it is possible to restore the hydrodynamic conditions of coastal zones in earlier eras.

Continuous fluctuations in the level of the Azov Sea contributed to the formation of the spits in their modern form. The regular nature of changes in the direction of alongshore currents leads to the accumulation of sediments at the ends of the spits. Catastrophic wind surges lift them, completing the body of the spit.

The isolation of the Azov Sea from tidal basins leads to the formation of a complex system of sea surface level fluctuations. Tides are directly discernible only using high-frequency spectral analysis [*Korzhenovskaia et al.*, 2022]. The visually observed diurnal and semi-diurnal sea level rises represent a superposition of waves of different natures. These include both lunar and solar tides, as well as radiation tides associated with winds. The bathymetric compartments of the Taganrog Bay are separated from each other by the underwater ends of the spits, which impede water exchange. Each compartment is characterized by its own oscillation systems – seiches. When eigen oscillations come into resonance with tidal ones, coastal level gauges record pronounced daily and semi-diurnal dependences of the water level.

Test calculations show that the classical tidal analysis program T_TIDE is applicable with caution for the Sea of Azov. Ocean tides have the character of forced waves, the period of which strictly corresponds to the period of the forcing forces. Regular rises in the level of the Azov Sea are formed by a combination of free oscillations at eigen frequencies. The share of regular, compelling, tidal forces that significantly feed seiches remains to be calculated. Changes in the wind regime reshape the periods of regular oscillations. For example, today the period of level peaks is 12 hours, tomorrow it can decrease to 9, and the day after tomorrow it can rise to 13 hours. At the same time, a general characteristic pattern is observed: the maximum water level at the top of the Taganrog Bay (Donskoy village) is observed in between 21:00 pm and 2:00 am. In conditions of constant wind with a speed of up to 5–7 m/s, or after a strong wind (more than 10 m/s) weakening, fluctuations in water level with an amplitude of up to 2 m can be completely explained by seiche dynamics. Single-node seiches of the Sea of Azov in the Taganrog Bay are observed infrequently. They are accompanied by extreme surges and maximum saturation of amphidromic sea systems with energy. In this case, the proportion of wave dynamics during level changes decreases. When the surge winds weaken, the diurnal dynamics of the level and currents are built. Accurate estimates require continued observations, filtering out low-frequency, biweekly fluctuations, and calculating the sea's energy balance.

The results of the work correspond to the known patterns of energy exchange between the atmosphere and the ocean. Even weak winds lead to the development of wave processes at eigen frequencies close to tidal ones. Increasing winds contribute to the intensification of wave fluctuations and significant transfer of water during strong surges.

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