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Climatic Fluxes of Bottom Sediments in the Sea of Azov

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Abstract
Purpose. The work is aimed at obtaining a general picture of sediment transport in the Sea of Azov over a climatic period.
Methods and Results. The research was carried out by the numerical modeling methods using modern hydrodynamic and wave models, as well as the sediment transport model that takes into account the combined effects of sea currents and wind waves. The Azov Sea hydrodynamic parameters for 42 years – from 1979 to 2020 – were calculated. The output database consists of the hourly spatial fields of the currents' velocities and directions on five σ -horizons, integral characteristics of the wind waves (heights, periods and directions of propagation), sea levels and the bottom matter fluxes. The total length of the array makes it possible to analyze in detail the individual hydrodynamic situations and seasonal features, and also to make climatic generalizations. The carried out studies resulted in obtaining a qualitative idea of the bottom sediments global (sea-scale) transport in the Sea of Azov.
Conclusions. Climatic features of the bottom sediment transport in the Sea of Azov are the following: 1) the main flux is formed as an extensive cyclone that covers the central part of the sea and involves bottom sediments from the western and eastern parts of the sea coast; 2) on the northern coast, near the tip of the Obitochnaya Spit, there are two flows: the first one, predominant, is from the Berdyanskaya Spit, and the second one, less pronounced, is from the Fedotov Spit; the resulting flux forms extensive shoals to the south of the Obitochnaya Spit; 3) the strongest fluxes are formed at the Berdyanskaya and Obitochnaya spits, as well as in the area of the Dolgaya Spit.

Keywords: mathematical modeling, Sea of Azov, currents, wind waves, sediment flows, bottom sediments

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Introduction

Morphological appearance of any water body is determined by its geological and lithodynamic features (bottom topography, composition and bottom sediment thickness), including a complex of external hydrodynamic factors that contribute to the redistribution of bottom sediments within the water area and the coastline formation. Thus, the construction of climatic spatial maps of bottom matter flows is of particular interest. These maps reflect the general directions of sediment movement. At present, there are no such generalizing maps (flux maps) for the Sea of Azov.

It should be noted that, over the past few decades, efforts of many specialists have resulted in obtaining interesting and important data on the structure of bottom sediments, the sedimentogenesis and sedimentation processes in the sea (research [1] and papers [1–3]). Separate studies of the resulting directions and magnitudes (i.e., values) of bottom material fluxes had a pronounced regional nature and were mainly associated with an analysis of the drifting mechanisms in ports and approach sea channels.

In general, sediment migration is a certain problem both in global tasks, on a scale of the entire sea (ensuring the safety of navigation), and in local ones (preserving the stability of beaches). Below there are some figures that enable to judge to some extent the sediment dynamics in the Sea of Azov basin. In 2019, the Ukrainian Sea Ports Authority (http://www.uspa.gov.ua) planned excavation works in the navigation channel area to the port of Berdyansk with a volume of 1.4 million m^3. In the port of Mariupol, the total volume of dredging required to return to the nominal draft is ~ 1.5 million m^3 [4]. The presented data, albeit indirectly, testify to the high mobility of bottom sediments.

Note that some regularities of the bottom sediment movement on a sea scale are given in [5, 6]. They indicate that most of the abrasive material formed as a result of the Sea of Azov coast erosion is transported in the form of suspended solids to the deep sea.

Consequently, the principal aim of the present paper is to obtain a general picture of the sediment movement in the Sea of Azov for the climatic period of 1979–2020. The main research method is mathematical modeling.

Materials and methods

The Sea of Azov is a relatively small body of water belonging to the Atlantic Ocean basin (Fig. 1). Surface area is ~ 39,000 km^2. The specific linear dimensions that make up the conventional length and width are 360 and 180 km, respectively; the mean depth of the sea is 7.5 m, the maximum is 13.5 m. The bottom of the sea center is a rather flat plain covered with soft silt; the depth in this part is 10–12 m [7]. Several sand spits (Belosaraiskaya, Berdyanskaya, Obitochnaya and Fedotov) depart from the steep northern coast in a southwestern direction. In the west, the coast is a continuous sandy spit (the Arabat Spit) with a width of several hundred meters in the south to 6–8 km in the north. The eastern coast is formed by

[1] Sorokina, V.V., 2006. [*Peculiarities of Terrigenous Sedimentation in the Sea of Azov in the Second Half of the 20th Century*]. Extended Abstract of PhD Thesis. Rostov-on-Don, 25 p. (in Russian); Ivlieva, O.V., 2007. [*Technogenic Sedimentogenesis in the Sea of Azov*]. Extended Abstract of Dr.Sci. Thesis. Rostov-on-Don, 48 p. (in Russian); Pol'shin, V.V., 2010. [*Patterns of the Formation of Modern Bottom Sediments of the Sea of Azov*]. Extended Abstract of PhD Thesis. Murmansk, 28 p.; Matishov, G.G., Golubeva, N.I. and Sorokina, V.V., eds., 2011. *Ecological Atlas of the Sea of Azov*. Rostov-on-Don: YUNTS RAN, 325 p. (in Russian).

a sand bar with several developed spits (Achuevskaya, Yasenskaya and Kamyshevatskaya). In the north, the shallow Taganrog Bay, elongated in a northeastern direction, is adjacent to the main water area.

The Sea of Azov is characterized by a mixed type of bottom sediments containing close proportions (25–40%) of silt, aleurite and sand fractions. This type of precipitation is most typical for coastal areas, the bases of large banks of the open sea, as well as the centers of bays.

The main factors determining the hydrodynamic regime of the Sea of Azov are sea currents, surface waves, seiche level fluctuations and storm surges. Under the conditions of a relatively shallow and insignificant sea size, these hydrodynamic factors are highly interrelated. For example, the degree of development of wind waves is determined by the stability in the direction and strength of the wind flux, the acceleration length and the area depth. In the Sea of Azov, the heights of the storm surges can be comparable with the depths. In 1969, as a result of a strong storm, an almost three-meter surge of water was observed in the Temryuk region, and a two-meter surge in Genichesk, the total level imbalance between Genichesk and Temryuk was about 5 m.

Another feature of the Sea of Azov is the ice field formation, which, depending on the severity of winters, can cover the entire sea area. This phenomenon significantly transforms the fields of currents and wind waves. Thus, the complex nature of the formation of the hydrodynamic regime of the Sea of Azov is obvious.

F i g. 1. Bathimetry map and morphometric features of the Sea of Azov

A correct description of the interaction mechanisms between sea currents, wind waves and storm surges is possible within the framework of numerical simulation. In 2021, the authors of the present article, using 3D hydrodynamic and spectral wave models, obtained the climatic characteristics of sea currents and surface waves in the Sea of Azov for 1979–2020 [8]. The main approaches used in modeling, are as follows:

1. Initial fields of atmospheric pressure, surface wind components and ice concentration are selected from the ERA5 global atmospheric reanalysis database distributed by the European Center for Medium-Range Forecasts (ECMWF) (https://cds.climate.copernicus.eu). The computational domain is limited by coordinates: in latitude – 45.25°–47.50°N, in longitude – 34.75°–39.50°E. The spatial resolution is the same in latitude and longitude and is 0.125 degrees, the time step is 3 hours for atmospheric pressure and wind fields, 1 day for ice concentration. The calculation grid is based on the bathymetric map of the Sea of Azov, built by specialists from the Southern Scientific Center of RAS [9].
2. The ADCIRC hydrodynamic model (The ADvanced CIRCulation model), based on the solution of shallow water equations using the finite element method. We use a 5-layer σ-coordinate three-dimensional version of the model. ADCIRC allows to control the processes of temporary drainage (due to surges) or flooding (as a result of surges) of adjacent coastal areas. The ADCIRC model has proven particularly successful in studies of extreme storm surges [10]. In the present case, the choice of a 5-layer model is a certain compromise between the need to take into account the main physical mechanisms of current generation and resource-intensive computational capabilities, which, as believed, is quite justified for describing the general nature of water movement. Consideration of the details of the vertical structure of currents requires a slightly different approach and is beyond the scope of this study.
3. Surface wave parameters are calculated using the MIKE 21 SW spectral wave model of the Danish Hydraulic Institute, which implements the main physical mechanisms of wind wave transformation. The model adaptation issues to the conditions of the Black and Azov seas are described in detail in [11].
4. Combining the models permits to take into account the interaction of surface waves and currents. Parameters of currents and level surges determined in the hydrodynamic model are used in the spectral wave model when calculating the parameters of surface waves. Radiation stresses generated by wave breaking processes and calculated by the wave model correct sea currents (mainly coastal ones) and are taken into account by the hydrodynamic model.

With the basic hydrodynamic parameters at hand, bottom material fluxes can be calculated. For this purpose, the approach proposed by

R. Soulsby [12], considering the transport of suspended and entrained material under the combined effects of currents and surface waves, is used. The flux of bottom sediments is described by the expression

$$Q = A_s \bar{U} \left[\left(\bar{U}^2 + \frac{0.018}{C_D} U_{rms}^2 \right)^{1/2} - \bar{U}_{cr} \right]^{2.4} (1 - 1.6\tan\beta), \qquad (1)$$

where the coefficient $A_s = A_{sb} + A_{ss}$; $A_{sb} = \frac{0.005h(d_{50}/h)^{1.2}}{[(s-1)gd_{50}]^{1.2}}$; $A_{ss} = \frac{0.012 d_{50} D_*^{-0.6}}{[(s-1)gd_{50}]^{1.2}}$; $\bar{U}$ is the velocity of current, m/s; U_{rms} is the *rms* orbital wave velocity, m/s; $C_D = \left[\frac{0.40}{\ln\left(\frac{h}{z_0}\right) - 1} \right]^2$ is the coefficient of friction; $\bar{U}_{cr} = 0.19 (d_{50})^{0.1} log_{10} \left(\frac{4h}{d_{90}} \right)$ is the threshold value of current velocity, m/s; β is the bottom slope; h is the depth, m; d_{50} and d_{90} are the 50th and 90th percentiles of particle diameter distributions, m; z_0 is the bottom roughness, m; s is the relative density of precipitation; g is the free fall acceleration, m/s^2; ν is the kinematic viscosity of water, m^2/s; $D_* = \left[\frac{g(s-1)}{\nu^2} \right]^{1/3} d_{50}$. According to the authors' recommendations, the roughness value is assumed to be 0.006 m.

Thus, the flux given by formula (1) determines the volume of soil particles (m^3) transferred per unit time (s) through 1 m of the bottom surface. Since the matter transfer direction is ultimately determined by the resulting flux direction, the matter flux in vector form is represented as

$$\boldsymbol{Q} = (\boldsymbol{Q_x}, \boldsymbol{Q_y}) = \left(|\boldsymbol{Q}| \frac{U_x}{|\boldsymbol{U}|}, |\boldsymbol{Q}| \frac{U_y}{|\boldsymbol{U}|} \right), \qquad (2)$$

where $\boldsymbol{Q_x}$, $\boldsymbol{Q_y}$ are the sediment flux components; $U = (U_x, U_y)$ is the current velocity vector; U_x, U_y are the current velocity components; $|\boldsymbol{Q}|$, $|\boldsymbol{U}|$ are velocity and flux modules. Let it be clear that the advantage of the three-dimensional hydrodynamic model is the possibility of using the near-bottom components of the current velocity, responsible for the bottom material movement. The vertically averaged current parameters do not take into account, for example, the formation of countercurrents under conditions of strong storm surges.

When modeling, a spatial map of bottom sediments of the Sea of Azov is used, published in the information system *Ecological Atlas of the Sea of Azov* [2], as well as in the monograph [2]. For the area of soil occurrence, indicated in the Atlas as "medium-fine-grained sand (fraction 1–0.1 mm is over 70%)", as well as "medium-grained sand (1–0.1 mm fraction – 50–70%)", the median particle diameter corresponds to medium-grained sand and

[2] Matishov, G.G., Golubeva, N.I. and Sorokina, V.V., eds., 2011. *Ecological Atlas of the Sea of Azov*. Rostov-on-Don: YUNTS RAN, 325 p. Available at: http://atlas.iaz.ssc-ras.ru/sitemap-ecoatlas.html [Accessed: 16 May 2022] (in Russian).

is 0.35 mm; in the mixed type of sediments, d_{50} = 0.15 mm (i.e., it is assumed that fine-grained sand dominates); in areas with a predominance of silt, d_{50} = 0.075 mm. Of course, all this can be taken as a rough approximation, but here we encounter both model limitations (transport of the same silts requires a slightly different approach) and the quality of the initial data. In any case, we believe that further possible improvements will be associated more with clarifications, but not with a radical revision of the scheme proposed.

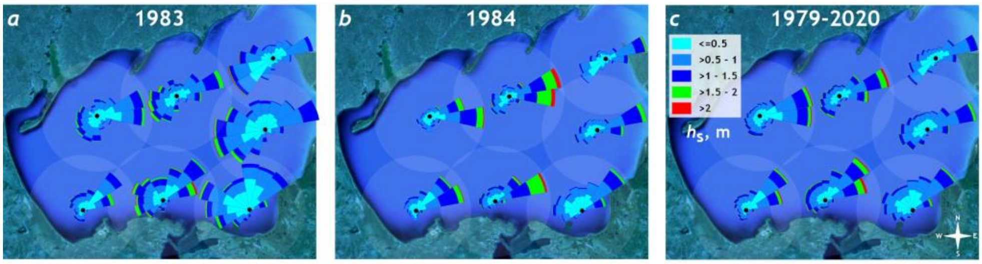
To calculate fluxes according to formula (1), another particle size corresponding to 90% of the distribution function of particle diameters (d_{90}) is required. Unfortunately, the necessary information about the distribution functions of particle diameters (much less their spatial variability) is missing. For this reason, we limit ourselves to estimated values. Following [13], which analyzes the granulometric composition of the bottom sediments of the Sea of Azov, as well as our own studies on the Dolgaya Spit, we assume that the size d_{90} is two to four times greater than the median size d_{50}. This being so, we will estimate that $d_{90} = 3d_{50}$.

The necessary calculations were carried out for 42 years – from 1979 to 2020. The output data array consists of hourly spatial fields of velocities and directions of currents on five σ-horizons, integral characteristics of wind waves (heights, periods and propagation directions), sea levels, as well as bottom sediment fluxes. Total length of the array enables to analyze in detail individual hydrodynamic situations, seasonal features and also to make climatic generalizations.

Results and discussion

In the shallow and limited in size Sea of Azov, the hydrodynamic regime nature is determined by the prevailing winds. At the same time, of course, the influence of local conditions, such as the coastline orientation, bathymetric features, river flow and possible ice cover, is noticeable. Northeastern and eastern winds generally prevail over the sea area with a total frequency over 45% [7]. It determines the pattern of mean long-term (climatic) fields of hydrodynamic parameters. Nevertheless, in some years, there is an increased frequency of winds of other sectors, in particular, southwestern ones, in other words, such dominance is not unconditional. For this reason, consideration both by climatic and some mean annual fields is not without interest.

Fig. 2 shows wind wave roses (in terms of significant wave heights) for several points in the Sea of Azov, taking into account only 1983 with an increased frequency of southwestern winds (a); only 1984 with a significant predominance of northeastern winds (b); the entire period of 1979–2020 (c).

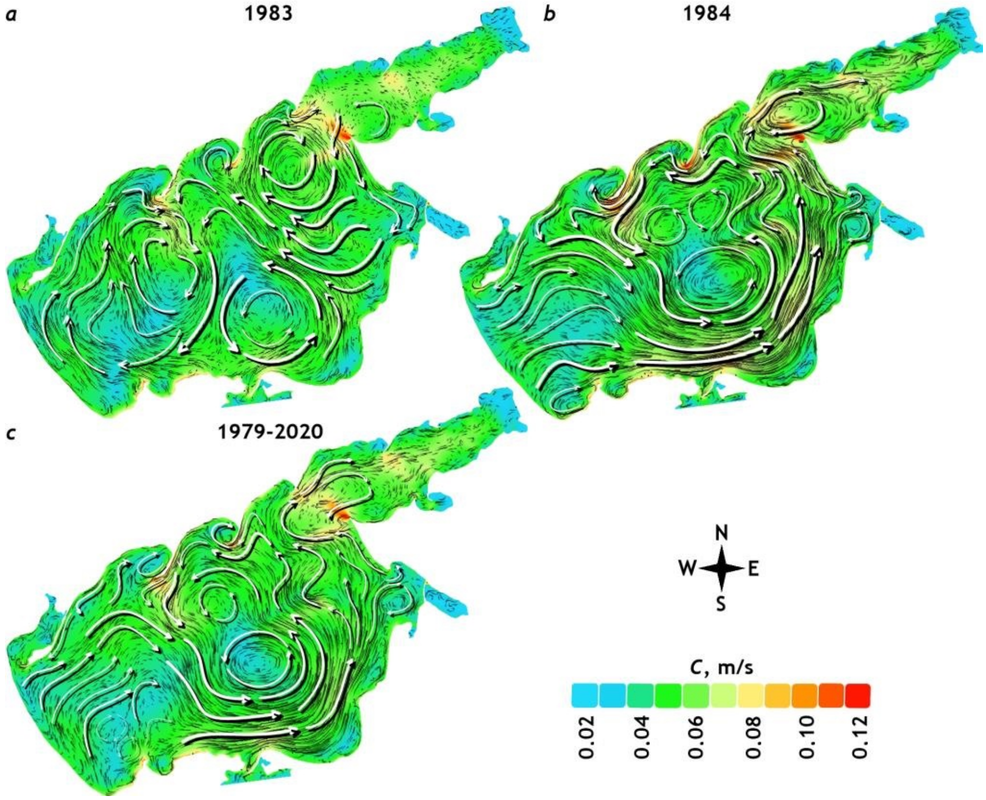


F i g. 2. Wind wave roses, m, for 1983 (*a*), 1984 (*b*) and 1979–2020 (*c*)

As follows from Fig. 2, the northeastern directions of waves are predominant in the climatic sense for almost the entire sea area. Contribution of southwestern storms is the most noticeable in the eastern part, which is determined primarily by the maximum possible lengths of wave acceleration. Extreme waves with significant wave heights exceeding 2 m are also associated mainly with northeastern winds and are observed in the central part of the sea. The increased frequency of waves in the northeastern directions is a consequence of the stability and duration of the air flux action in these directions. As a rule, the northeast wind is associated with the vast Azores anticyclone action, which covers the entire European part and determines wind conditions for a long time.

Once again, we note that the Sea of Azov peculiarity is its shallow water and relatively small size. As a result, there is a rapid response to changing atmospheric conditions, namely the prevailing wind direction and strength, as well as its spatial variability. In addition, significant level distortions caused by surge phenomena contribute to the circulation development in the vertical plane and can lead, for example, to countercurrents in the coastal zone. The use of a three-dimensional hydrodynamic model enables to analyze near-bottom currents that are important from the viewpoint of bottom sediment dynamics. Fig. 3 shows maps of near-bottom currents averaged over 1983 (Fig. 3, *a*), 1984 (Fig. 3, *b*) and for the entire period of 1979–2020 (Fig. 3, *c*).

The Fig. 3 data show that the dominance of northeastern winds (Fig. 3, *b*) contributes to the intensification of bottom currents in the coastal zones of the northern, southern and eastern parts of the sea, in other words, almost along the entire perimeter. An extensive cyclone forms in the central part of the sea. In the western part of the sea, in the bottom layer, there is an outflow of water from the Arabat Spit towards the open sea, caused by surge waves. With an increase in the influence of southwestern storms (Fig. 3, *a*), a similar pattern of near-bottom countercurrents is found near the eastern coast. Furthermore, the winds of the southwestern sectors form an anticyclonic circulation, covering the entire western part of the sea and somewhat weaken the cyclonic formation in the sea center.

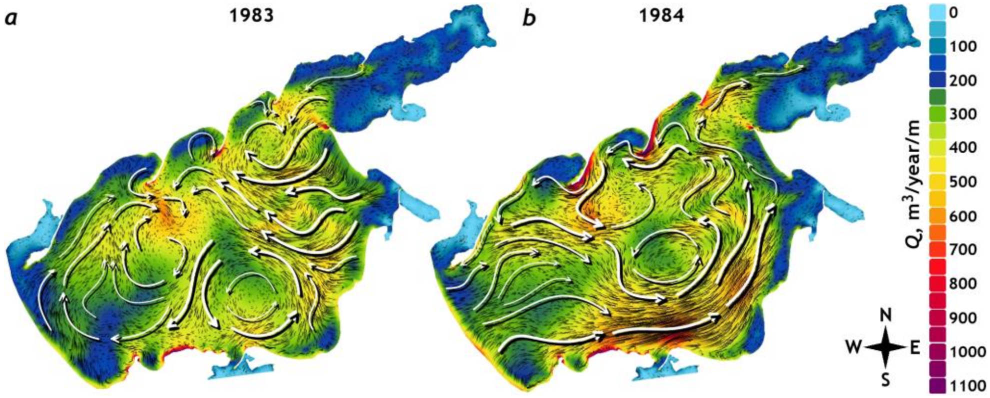


F i g. 3. Fields of the Azov Sea bottom currents averaged over 1983 (*a*), 1984(*b*) and 1979–2020 (*c*)

Let’s highlight the main features of the climatic near-bottom water circulation in the Sea of Azov (Fig. 3, *c*):

– an extensive cyclonic circulation dominates in the central part of the sea;
– an underdeveloped anticyclone is formed in the western part; the general transfer of waters is directed from the Arabat Spit towards the open sea;
– the highest velocities of alongshore currents are observed in the northern part of the sea in the area of the Berdyanskaya and Obitochnaya spits, as well as in the strait between the main part of the sea and the Taganrog Bay.

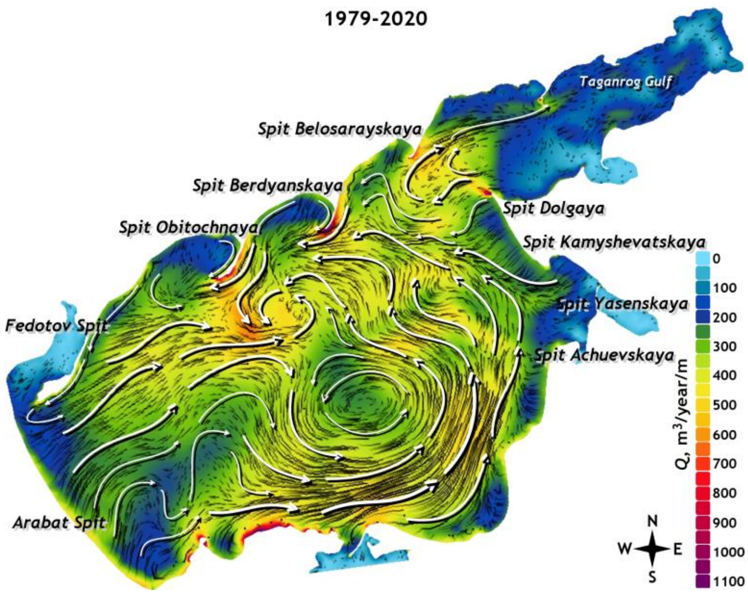
Having at our disposal an array of the necessary parameters of bottom currents and wind waves, we can proceed to estimates of bottom material currents in the Sea of Azov. Fig. 4 shows the mean annual spatial fields of bottom sediment fluxes for 1983 (Fig. 4, *a*) and 1984 (Fig. 4, *b*).



F i g. 4. Annual average fluxes of bottom sediments, m^3/year/m, for 1983 (*a*) and 1984 (*b*)

According to Fig. 4, there is one characteristic feature of the global (on the entire sea scale) sediment transport, independent of the predominance of certain atmospheric conditions. It's about the cyclonic type of movements characteristic of the central part of the sea. The dominance of winds of northeastern or southwestern directions causes the predominant transport of bottom sediments towards the open sea from the western (Fig. 4, *b*) or eastern (Fig. 4, *a*) coasts, respectively.

Climatic bottom material fluxes, as a result of the generalization of data for 1979–2020, are shown in Fig. 5.



F i g. 5. Climatic fluxes of bottom sediments (m^3/year/m)

The Fig. 5 data demonstrate the climatic features of bottom sediment transport in the Sea of Azov:

– the main stream is formed as a vast cyclone covering the central part of the sea with two most probable gyre centers;

– bottom sediments from the western and eastern coastal parts of the sea are involved in this cycle;

– on the northern coast, near the extremity of the Obitochnaya Spit, two streams meet: the predominant one – from the Berdyanskaya Spit side, and the less pronounced one – from the Fedotov Spit side. The resulting flux forms vast shallows south of the Obitochnaya Spit;

– along the Arabat Spit, transverse transport towards the sea dominates, which, quite possibly, explains its relative stability. A similar pattern is observed in the extended section of the eastern coast, between the Dolgaya and Kamyshevatskaya spits, as well as to the south of the Achuevskaya Spit;

– the strongest sediment fluxes are formed near the Berdyanskaya and Obitochnaya spits, as well as in the Dolgaya Spit area.

Note that when analyzing the results, we deliberately do not touch upon quantitative estimates of the fluxes (although they are shown in the figures) for several reasons. First, the correct specification of the initial data (in our case, maps of bottom sediments) is critically important in modeling. Sands and silts taken into account in the model for different parts of the sea have different percentages of other rocks, silts or shells, which inevitably affects their ability to be transported. Accounting for all these points is not a trivial task. Secondly, the flux modeling approach used is only one of the possible ones, with its own limitations and assumptions. And finally, the last point to be made. Any model calculations should be supported by observational data, which, in our case, are practically non-existent. Of course, one can use indirect criteria, for example, the rate of sedimentation, but even in this case, taking into account the accuracy of the method, we will deal only with orders of magnitude. Thus, we are quite confident in the **qualitative** picture of the transport of bottom sediments obtained and understand the debatability of **quantitative** estimates.

Conclusion

The principle aim of the paper was to obtain a general picture of the sediment movement in the Sea of Azov for a climatic period of time. The studies were carried out by numerical simulation methods using modern hydrodynamic and wave models, as well as a sediment transport model that takes into account the combined effect of sea currents and wind waves.

The hydrodynamic parameters of the Sea of Azov were calculated for 42 years – from 1979 to 2020. The output data array consists of hourly spatial fields of velocities and directions of currents on five σ-horizons, integral characteristics of wind waves (heights, periods and propagation directions), sea levels, as well as bottom matter fluxes. The total length of the array enables to analyze in detail individual hydrodynamic situations, seasonal features and also to make climatic generalizations.

Main results are as follows:

1. For almost the entire sea area, the northeastern directions of waves are predominant. Extreme waves with significant wave heights exceeding 2 m are also associated mainly with the northeastern sectors of waves and are observed in the central part of the sea.

2. Peculiarities of climatic near-bottom water circulation: 1) extensive cyclonic circulation dominates in the central part of the sea; 2) an underdeveloped anticyclone is formed in the western part; 3) the highest speeds of alongshore currents are observed in the northern part of the sea in the area of the Berdyanskaya and Obitochnaya spits, as well as in the strait between the main part of the sea and the Taganrog Bay.

3. Climatic features of bottom sediment transport in the Sea of Azov: 1) the main flux is created in the form of an extensive cyclone covering the central part of the sea, which involves bottom sediments from the western and eastern coastal parts of the sea; 2) on the northern coast, near the Obitochnaya Spit extremity, two streams meet: the predominant one – from the Berdyanskaya Spit side, the less pronounced one – from the Fedotov Spit side. The resulting flux forms vast shallows south of the Obitochnaya Spit; 3) the strongest streams are formed near the Berdyanskaya and Obitochnaya spits, as well as in the Dolgaya Spit area.

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Contribution of the co-authors:

Boris V. Divinsky – formulation of the goals and objectives of the study; analysis of materials on the research topic; correction of the mathematical model and carrying out calculations; processing and description of research results; preparation of the initial version of the text

Ruben D. Kosyan – initiation of research; general scientific management of research; analysis and generalization of research results; revision of the text

The authors have read and approved the final manuscript.
The authors declare that they have no conflict of interest.