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Original paper

Upwelling in the Black Sea Water Area near Cape Lukull Based on Numerical Modeling and Observational Data

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Abstract

Based on numerical modeling methods (a generalized three-dimensional barotropic linear model of Felsenbaum was used for the case of taking into account Rayleigh friction), the paper considers features of the structure of the current vectors field depending on wind conditions in an upwelling situation in the water area located along the northern coast of the Sevastopol seaside, between Capes Lukull and Tolsty. A two-layer transverse cell of water circulation, typical of upwelling, was identified. The currents were predominantly oriented downwind in the upper layer and in the opposite direction in the bottom layer. It is shown that in the analyzed water area upwelling was caused by northerly, north-easterly, easterly and south-easterly winds. Upwellings caused by the above winds differed in their location and area. Under a north-easterly wind, upwelling was most intense and widespread throughout the water area under consideration. Under a south-easterly wind, upwelling was formed in two small areas: in the bends of the coast, between Capes Margopulo and Lukull and north of Cape Tolsty. The modeling result was compared with data from expeditionary research. Their good agreement under a northerly wind was found.

Keywords: wind, currents, upwelling, numerical modeling, thermohaline structure, cape Lukull, Black Sea

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Апеллинг в акватории Черного моря у мыса Лукулл на основе численного моделирования и данных наблюдений

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Аннотация

На основе методов численного моделирования (использована обобщенная на случай учета рэлеевского трения трехмерная баротропная линейная модель Фельзенбаума) рассмотрены особенности структуры поля векторов течений в зависимости от ветровых условий в ситуации апвеллинга в акватории, расположенной вдоль северного берега Севастопольского взморья, между м. Лукулл и Толстый. Выявлена типичная для апвеллинга двухслойная поперечная ячейка циркуляции вод. В верхнем слое течения ориентированы преимущественно по ветру, в придонном слое – в обратном направлении. Показано, что в анализируемой акватории апвеллинг вызывают северные, северо-восточные, восточные и юго-восточные ветры. Апвеллинги, обусловленные указанными ветрами, различаются локацией и площадью очага. В условиях северо-восточного ветра апвеллинг наиболее интенсивный и распространен во всей рассматриваемой акватории. При юго-восточном ветре апвеллинг формируется на двух небольших по площади участках – в изгибах берега между м. Маргопуло и Лукулл и севернее м. Толстого. Результат моделирования сопоставлен с данными экспедиционных исследований. Обнаружено их хорошее соответствие при северном ветре.

Ключевые слова: ветер, течения, апвеллинг, численное моделирование, термохалинная структура, мыс Лукулл, Черное море

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Introduction

Upwelling is a typical phenomenon in the oceans and seas. Its types on different spatial and temporal scales are quite well studied, with the results reflected in numerous publications. These include, for example, works [1–6] based on the analysis of experimental contact and satellite data and studies [7, 8] using numerical modeling methods. The results of the study of upwelling are important in terms of application and are widely used in various branches of marine science.

According to [9], surge phenomena (wind upwelling and downwelling, respectively) are typical for Sevastopol bays and open areas of the seaside. Upwelling in the considered small coastal water area is investigated for the first time, it is interesting and significant in fishery terms. According to the results of the Black Sea fishery monitoring [10], dense accumulations of sprat are formed in this area during upwelling, which are successfully fished by trawlers of medium tonnage.

Objectives of the article are as follows:

– on the basis of numerical modeling, to reveal regularities of the structure of the local current system under upwelling depending on wind conditions in the water area located along the northern coast of the Sevastopol seaside between capes Lukull and Tolsty;

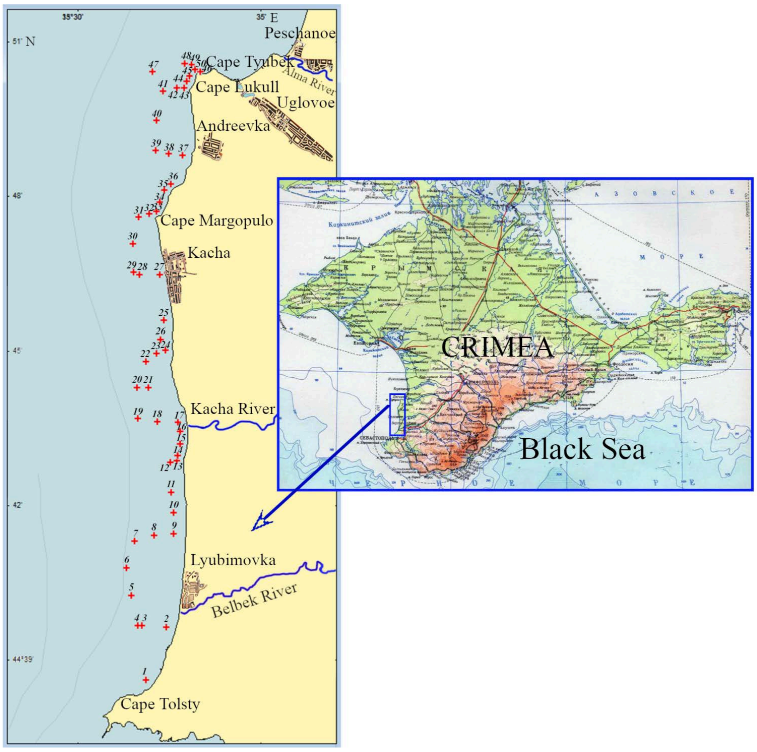
– to estimate the intensity of upwelling;

– to compare the modeling result with data from expeditionary research.

The study area is a coastal zone of about 12 miles along the northern coast of the Sevastopol seaside located between capes Lukull and Tolsty (Fig. 1).

The bold coast is one of the main morphometric features of the water area under consideration, which determines water dynamics. The coastal shallow water area is bounded by a rather pronounced shelf edge.

It is known that in areas with similar bottom relief, upwelling and downwelling are formed both under the influence of winds having a normal component relative to the coastline and under the influence of wind flows directed at an acute angle to the coast.



F i g . 1 . Geographical location of the study area and survey station map of the survey performed by Marine Hydrophysical Institute in September 2019

Background data and research methods

Problem statement

Wind currents prevail in Sevastopol bays and on the open seaside areas [11, 12]. Therefore, a generalized three-dimensional barotropic linear model [1)] of Felsenbaum was used for the case of taking into account Rayleigh friction to calculate the characteristics of currents [12]. It should be noted that numerical modeling of hydrological processes in such basins is traditionally used by domestic [13, 14] and foreign [15–17] authors to understand the regularities revealed on the basis of *in situ* observation data.

Taking into account that the currents undergo the reorganization on the shelf rather quickly taking into account the wind influence (approximately within a day), we will calculate the average currents in the framework of the steady-state currents theory. The proposed model takes into account the main factors influencing the currents, such as Coriolis force, bottom relief, coast configuration, wind action (direction, intensity and spatial irregularity), bottom and internal friction.

The following equations represent the linear theory of steady-state currents in a homogeneous fluid, taking into account the internal friction proportional to the current velocity

$$-fv = g\varsigma_x + Au_{zz} - ru, \qquad fu = g\varsigma_y + Av_{zz} - rv,$$

$$u_x + v_y + w_z = 0.$$

Here, f is Coriolis parameter; u, v, w are current velocity components; g is gravity acceleration; ς is downgrade; A is kinematic coefficient of vertical viscosity; r is internal friction coefficient.

At the sea surface, which is defined as a current surface, the tangential wind stress is balanced by turbulent friction in the seawater, so that

$$\text{at } z = 0 \qquad Au_z = -\tau_x, \qquad Av_z = -\tau_y, \qquad w = 0,$$

where τ_x, τ_y are components of tangential wind stress related to seawater density.

On the bottom, the condition of adhesion is assumed, on the solid boundaries of the basin (on the coast) – the condition of non-flow, on open liquid boundaries – the condition of free flow.

The solution of the three-dimensional currents problem is reduced to the solution of the two-dimensional problem for the integral current function. The components of the current velocity are calculated using analytical formulae, which makes it possible to carry out calculations on a relatively fine grid and describe the features of coastal and bay currents. The calculation is performed layer-by-layer for eight main directions of moderate winds with a velocity of 7 m/s under real bottom topography conditions. Details of the algorithm and the parameters used are given in work [1)].

[1)] Felsenbaum, A.I., 1960. [*Theoretical Foundations and Methods of Calculating Steady-State Sea Currents*]. Moscow: Izd-vo AN SSSR, 126 p. (in Russian).

Observation data

To confirm the representativity of the results of the numerical experiment, we used the data from the survey conducted by the Marine Hydrophysical Institute (MHI) on 17 September 2019 in a northerly wind. Four other surveys of the Sevastopol seaside area under consideration, the data of which we have at our disposal, were carried out in calm and low-wind weather.

According to the *Wetterzentrale* hydrometeorological center data (available at: http://old.wetterzentrale.de/topkarten/fsreaeur.html), the synoptic situation over the Black Sea during the first and second ten-day periods of September 2019 was determined by the eastern periphery of the Azores High. A moderate northerly wind with an average daily speed of 4–7 m/s was observed over the study water area.

The survey was carried out according to a scheme that included 47 drift stations (Fig. 1). The sampling works were carried out from the board of small-sized vessel *Gladiator*. The investigated depths ranged from 4 to 37 m. The array of initial empirical information was formed with the help of a *Condor* sounding complex [2)]. Temperature, salinity and other parameters of the aquatic environment were measured *in situ* in the probing mode with a depth step of 0.1 m. The accuracy of temperature determination is ±0.01°C, that of salinity – ±0.005 PSU. The ideas about real water circulation under the action of a northerly wind were obtained on the basis of an indirect method – analysis of the structure of temperature and salinity fields.

Results and discussion

As shown by the results of the modeling experiment, upwelling was observed in four of the eight calculation variants corresponding to the northerly, north-easterly, easterly, south-easterly wind directions.

Under these winds, a two-layer transverse circulation cell characteristic of upwelling was revealed, manifested by the outflow of water from the coast to the sea in the upper layer and the compensatory flow in the bottom layer. Upwelling zones (centers) were identified in the calculated field of current vectors in the bottom layer by the position of flows directed along the normal to the coastline (Figs. 2–5).

Let us consider the structure of the local current system for each of the wind directions indicated above.

In the upper water layer, the calculated vector fields had the same property irrespective of the wind direction. The currents were oriented predominantly downwind and had a velocity of 5–25 cm/s (Figs. 2–5).

Northerly wind (Fig. 2). A southward-directed flow along the coast is observed in the upper water layer.

At the bottom in the seaward area, the current is directed north-eastwards. With the approach to the coast, this flow turns clockwise, causing the bottom water

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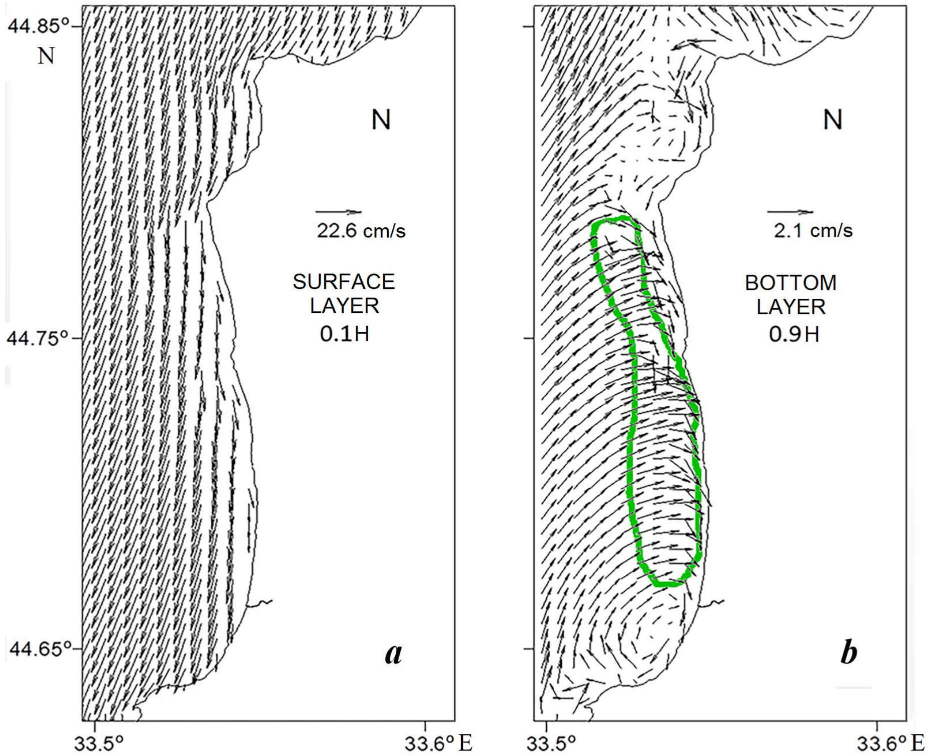
[2)] Available at: http://ecodevice.com.ru/ecodevice-catalogue/multiturbidimeter-kondor [Accessed: 29 April 2024].



F i g . 2 . Currents vectors in the surface (*a*) and bottom (*b*) layers under a northerly wind. The upwelling area is contoured in green

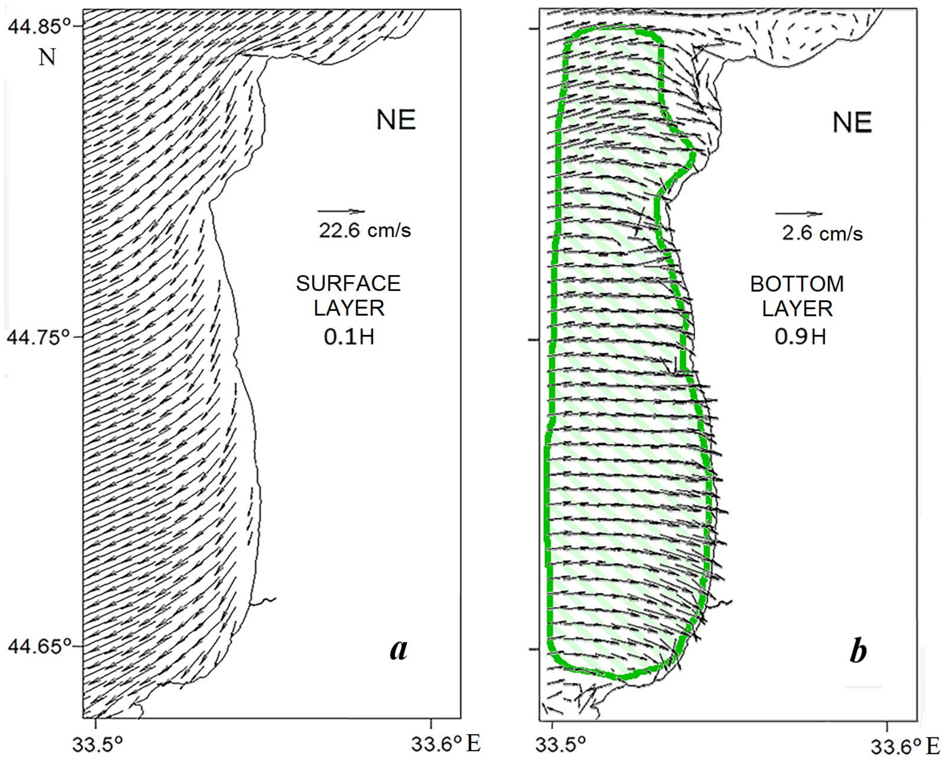
to move to the shallower waters where the longshore jet of the southward current is formed.

An upwelling zone of ~6 square miles (6 miles long and 1 mile wide) is located along a straight stretch of the coastline, between capes Margopulo and Tolsty. Two anticyclonic vortex cells are observed north and south of the upwelling area in the bends of the coastline. One of them is in the coast bend between capes Margopulo and Lukull and the other – to the north of Cape Tolsty (Fig. 2, *b*).

North-easterly wind (Fig. 3). Under this wind in the upper layer in shallow water, the current washes the coastline and is directed south-south-west. As it moves away from the coast, it deflects to the west-south-west (Fig. 3, *a*).

In the bottom layer throughout the entire water area, the current is directed along the normal to the coast, providing maximum transport, uplift and distribution of bottom water in shallower waters. The upwelling zone has a maximum area of ~36 (12 × 3) square miles and is distributed throughout the analyzed water area. Longshore currents jets and vortex cells are not observed (Fig. 3, *b*).

Upwelling is most intense in this wind situation.



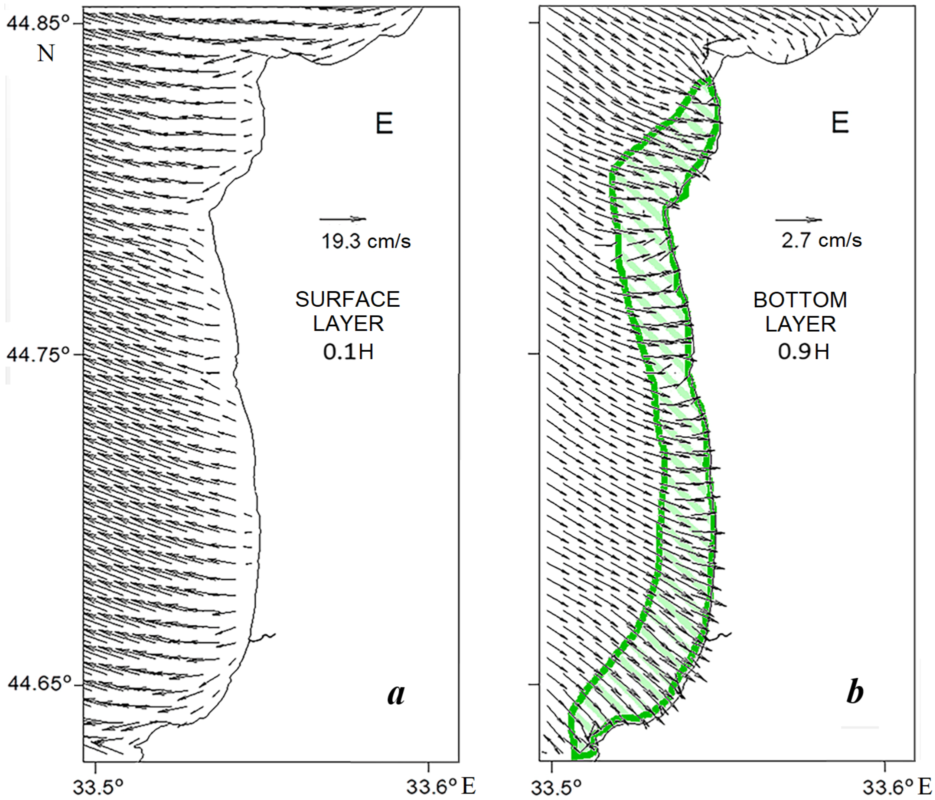
F i g . 3 . Currents vectors in the surface (*a*) and bottom (*b*) layers under a north-easterly wind. The upwelling area is contoured in green

Easterly wind (Fig. 4). Under the action of this wind, the current is directed downwind with a slight deflection to the left in the upper water layer.

At the bottom in the seaward area, the current is directed south-eastwards and to the coast in shallow water. Upwelling is not as intense as in the north-easterly wind action situation because the transport of water normal to the coast is concentrated in a narrower coastal strip of ~11 (11 × 1) square miles. No pronounced longshore flow jets and vortex cells are observed (Fig. 4, *b*).

South-easterly wind (Fig. 5). Under this wind, the current follows a north-north-westerly direction in the upper sea layer.

Upwelling is formed in two small areas - in the bends of the coast north of Cape Tolsty and between capes Margopulo and Lukull. Here, the south-easterly wind vector is orientated along the normal to the coastline and two small centers



F i g . 4 . Currents vectors in the surface (*a*) and bottom (*b*) layers under an easterly wind. The upwelling area is contoured in green

of upwelling develop due to the wind seiche. The area of each of them is estimated to be 2–3 square miles (Fig. 5).

Fig. 6 shows temperature and salinity distribution in the surface sea layer of the study water area under a moderate stable northerly wind. The distribution is based on data from the MHI expedition conducted on 17 September 2019.

Comparison of the elements of the thermohaline structure of waters (Fig. 6) with the result of numerical experiment (see Fig. 2) shows their good agreement.

In the straight-line section between capes Margopulo and Tolsty, a coastal strip of waters with a 0.6–0.8°C lower temperature relative to the ambient background is clearly visible, which could be the result of upwelling.

Local extremes of temperature and salinity were observed in the bend of the coastline to the north of Cape Tolsty, which indicates indirectly the presence of a vortex cell in this area.

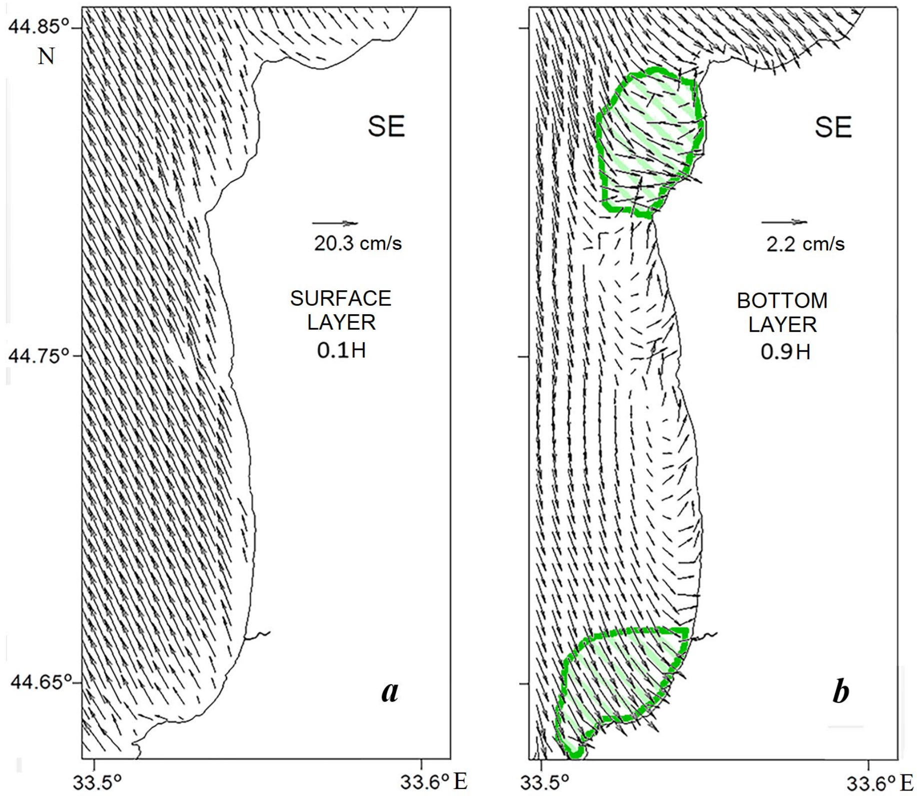
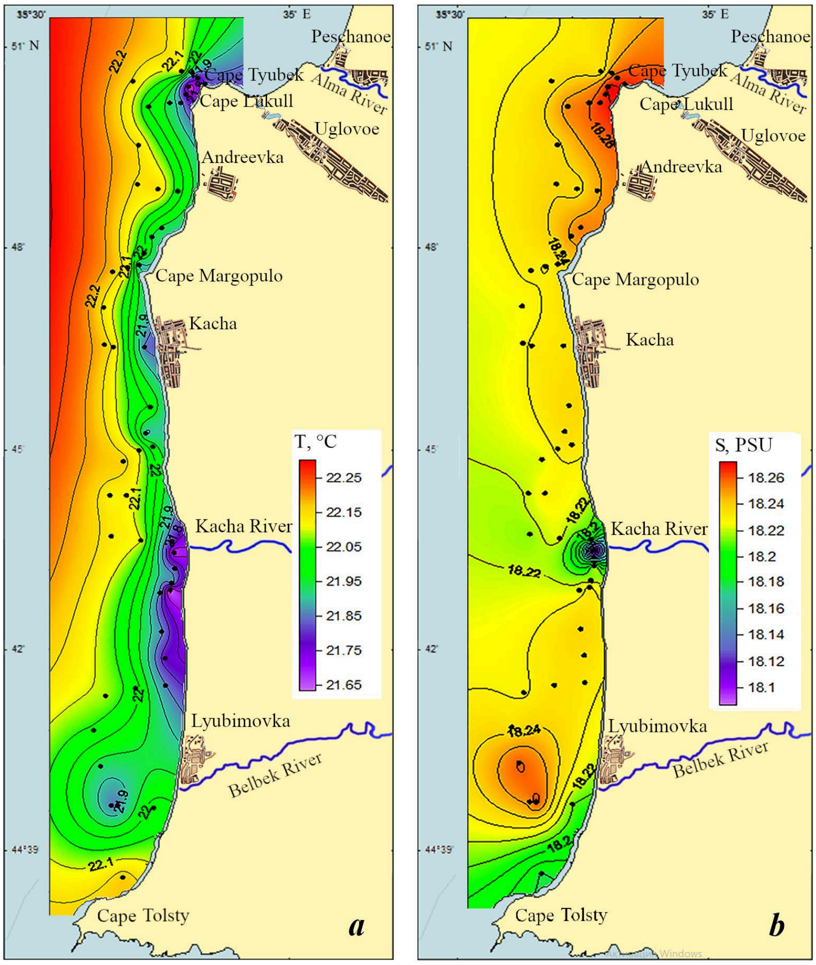


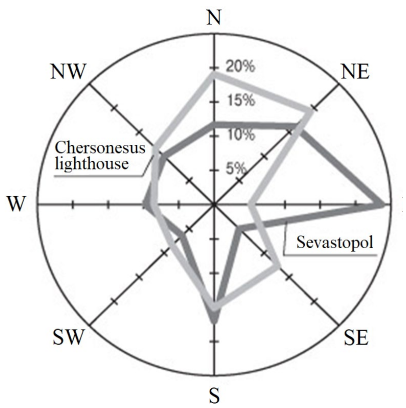
Fig. 5. Currents vectors in the surface (*a*) and bottom (*b*) layers under a south-easterly wind. The upwelling area is contoured in green

The numerical experiment yielded results indicating that wind upwelling was a prevalent phenomenon in the water area of the Sevastopol seaside, observed during a substantial portion of the year. According to the wind rose of the Sevastopol region, the total frequency of upwelling winds identified during the entire year is 49% (Fig. 7).

According to the data of the integrated monitoring of the fishing situation in the Black Sea, in the area of Cape Lukull (including the study area), dense accumulations of sprat (harvested by the fishing fleet) are formed in summer during the development of upwelling. At the same time, the hydrodynamic characteristics and water temperature regime are reliable enough to predict fishing conditions 5–7 days in advance [10].



F i g . 6 . Distribution of temperature (*a*) and salinity (*b*) in the surface sea layer under a moderate stable northerly wind on 17 September 2019



F i g . 7 . Wind rose of the Sevastopol region (Adopted from: https://sevastopol.press/2007/05/24/v-kakuju-storonu-veter-duet/)

The results of this study can be used to predict the quality of the fishing situation for sprat in the study area on the basis of wind forecasts. Northerly and south-easterly winds, causing upwelling, create more favourable conditions for fishing compared to winds of other directions.

Conclusion

Based on the numerical modeling, the paper considers peculiarities of upwelling in the coastal waters of the Sevastopol seaside between capes Lukull and Tolsty.

The analysis demonstrates that northerly, north-easterly, easterly and south-easterly winds induce upwelling in the study area. The upwelling caused by these winds varies in terms of location and focus area.

The northerly wind causes upwelling on a straight section of the coastline between capes Margopulo and Tolsty with a center area of 6 square miles. Two anti-cyclonic vortex cells are formed in the bends of the coast between capes Margopulo and Lukull and to the north of Cape Tolsty.

Under the action of the north-easterly wind, upwelling is the most intense and widespread in the entire water area under consideration. Its area is estimated at 36 square miles.

The easterly wind causes upwelling, well pronounced but less intense compared to the conditions determined by the north-easterly wind. Its center occupies a narrower coastal strip of the whole water area under consideration – 11 square miles.

Under the south-easterly wind, upwelling is formed only in two small areas (2–3 square miles), in the bends of the coast between capes Margopulo and Lukull and to the north of Cape Tolsty.

The modeling experiment with the northern wind was compared with the result of the analysis of the thermohaline field structure based on the materials of the MHI expedition carried out under similar wind conditions. The following results of the study were confirmed during the comparison: an upwelling center was identified in the rectilinear section of the water area under study and a vortex cell was detected in the bend of the coastline to the north of Cape Tolsty.

The analysis demonstrates that wind upwelling is a characteristic phenomenon for the northern part of the Sevastopol seaside, observed during 49% of the entire year.

The results of this study can be used to predict the quality of the fishing situation for sprat in the study area based on wind forecasts. The prevailing winds in the northern and south-eastern sectors, which cause upwelling, create more favourable conditions for fishing when compared to winds from other directions.

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Contribution of the authors:

Pavel D. Lomakin – general task statement, selection and interpretation of field data, general result interpretation, article writing

Yuri N. Ryabtsev – carrying out numerical experiments, modelling results interpretation, general result interpretation

Alexey I. Chepyzhenko – organization and carrying out the expedition, observational data processing and analysis, general result interpretation

All the authors have read and approved the final manuscript.