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ORIGINAL RESEARCH ARTICLE

Parameters of wind seas and swell in the Black Sea based on numerical modeling

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Summary The main objective of our work is to estimate the climatic peculiarities of the distribution of wind sea and swell in the Black Sea. The method of our research is numerical modeling. We tuned the spectral wave model DHI MIKE 21 SW for automatic separation of the components of surface waves. We estimated the peculiarities of the spatial distribution of the power of wind seas and swell in the basin of the Black Sea in the last 10 years (2007—2016). We determined the regions of domination of wind seas and swell in the field of mixed waves.
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1. Introduction

1.1. General notes

Two main components can be usually distinguished in the structure of surface waves: wind seas and swell. The development of wind seas is immediately related to the local wind field. Swell is related to the waves propagating beyond the zones of their generation, or the phase velocity of these waves exceeds the wind speed (for example, US Army Corps of Engineers, 2002). In the open ocean, swell can propagate over hundreds or even thousands of kilometers. The characteristics of swell in the Black Sea are limited by the geographical size and closeness of the sea basin.

Usually, the characteristics of wave field are presented as a set of integral parameters (significant wave height, mean

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period, general direction of propagation). Such an approach is justified in the case of one-dimensional wave field. If the wave spectrum is formed as a result of interaction between several wave systems it is reasonable to obtain separate wave characteristics for each of these systems.

Besides the fundamental scientific interest to the problem, separation of the wave field into individual components makes it possible to:

- more correctly describe the spatiotemporal structure of surface waves;
- efficiently calculate wave loads on the off- and onshore constructions and forecast hazardous phenomena in closed basins (low-frequency oscillations);
- clarify the schemes of redistribution and transport of bottom sediments;
- improve prognostic estimates of the wave situations for navigation at sea.

Currently, the information about the characteristics of mixed waves and swell is presented within a number of projects of the global reanalysis, for example, European Centre for Medium-Range Weather Forecasts ECMWF (Dee et al., 2011). The results of the recent researches performed on the basis of similar data sets made possible to estimate the climatic peculiarities of the distribution of swell on the oceanic scale (Bitner-Gregersen, 2015; Chong and Chong, 2017; Ewans et al., 2006; Kaiwen et al., 2015; Loffredo et al., 2009; Portilla et al., 2015; Semedo et al., 2011). Application of swell parameters from the database of reanalysis seems incorrect in the Black Sea because the time interval of such data is 3 h. A set of characteristics of storm activity in the Black Sea was investigated in Boukhanovsky and Lopatoukhin (2015). It was shown in particular, that the mean duration of storms is 14–25 h depending on the predefined threshold level. This is the cause that the time interval of the output fields of wind waves is obviously insufficient for the synoptic conditions of the Black Sea.

There are not so many publications on the separate description of surface wave components in the Black Sea. The authors of Bukhanovsky et al. (2000) made an attempt to construct climatic spectra for individual classes of waves in the northeastern part of the Black Sea. The analysis was based on the experimental data published in Kos'yan et al. (1998). The recurrences of climatic spectra for wind seas, swell, and mixed waves were estimated at 43%, 32%, and 25%, respectively. Characteristics of wind seas and swell based on the data of the ECMWF reanalysis in the southern part of the Black Sea in the period from October 1, 2000 to February 28, 2006 with an interval of 12 h were analyzed in the dissertation by Berkün (2007). Such an analysis can be considered only as an estimate due to the cause mentioned above. One of the recent publications is Van Vledder and Akpinar (2016). Unfortunately, by the time our paper has been prepared, this manuscript was available only in the form of a thesis. Therefore it is difficult to make comments.

1.2. Methods of separating of wave components

Calculation of integral wave characteristics with the account for the mixed waves is usually related to the analysis of the power spectra of surface waves or physical conditions of wave propagation.

Several approaches are applied depending on the available data:

- Analysis of one-dimensional frequency spectrum.

Separation frequency f_{sep} is selected in the wave spectrum; it is assumed that the interval of the power spectrum below this frequency corresponds to swell, and the interval of higher frequencies corresponds to wind seas. Then, the curve of spectral density $S(f)$ is integrated and, for example, significant heights of wind seas and swell are determined:

$$H_{s,swell} = 4\sqrt{\int_{f_l}^{f_{sep}} S(f)df}, \quad H_{s,wind} = 4\sqrt{\int_{f_{sep}}^{f_u} S(f)df},$$

where f_l, f_u are the lower and upper integration frequencies.

Frequency f_{sep} can be specified as a constant or function $f_{sep} = 0.8f_{PM}$, where f_{PM} is the frequency of the Pierson–Moskowitz spectrum peak corresponding to the full developed waves (Pierson and Moskowitz, 1964). Frequency f_{PM} is determined by relation $f_{PM} = 0.14g/U_{10}$, where U_{10} is wind velocity at a height of 10 m, g is the acceleration due to gravity. The separation frequency can be also determined from the analysis of wave steepness (Wang and Hwang, 2001) on the basis of the fact that wind seas are steeper than swell and that the maximum steepness is observed in the vicinity of the spectrum maximum.

- Application of the criterion that takes into account the wave age.

The wave component is considered swell if the following condition is satisfied (Bidlot, 2001):

$$\frac{U_{10}}{c}\cos(\theta - \theta_w) < 0.83,$$

where c is the phase velocity of waves, θ, θ_w are the directions of waves and wind, respectively.

- Analysis of two-dimensional frequency-directional spectrum.

The frequency-directional spectrum contains full information about the structure of surface waves. Determination of the main characteristics is performed by integration of individual parts of the two-dimensional spectrum corresponding to the wave systems. We focus attention on publication by Portilla et al. (2009), in which the authors suggested an automatic method of wave separation considering a two-dimensional spectrum as a watershed chart, which makes possible detection of the entire set of the wave systems.

A brief conclusion. If the frequencies of swell and wind seas are quite close, the efficiency of separation using only the frequency spectrum is extremely low. These approaches operate in the case of distinct separation of wave components. Analysis of the frequency-directional spectrum due to its completeness seems a more correct method of separation.

1.3. Goals of our research

The main goal of our research is the assessment of climatic peculiarities of the distribution of wind seas and swell over the Black Sea basin. Let us formulate the main objectives:

- analyze the capabilities of the MIKE SW model to automatically separate wind seas and swell;
- determine optimal tuning of the spectral wave model for automatic separation of wave components;
- obtain separate integral characteristics of the components of surface waves based on the experimental data;
- investigate the features of spatial distribution of the power of wind seas and swell in the basin of the Black Sea during the last 10 years (2007—2016).

2. Separation methodology

In this section, we shall briefly describe the model we used, as well as the experimental data, and physical aspects of modeling. It is noteworthy that absolute separation of the experimental wave field into individual components can be done very rarely. More frequently we deal with mixed waves formed under the influence of numerous external and internal factors. Unambiguous interpretation of the frequency-directional spectrum is hardly possible in such situations; therefore, one would not avoid subjectivity in conclusions.

2.1. Numerical model

In this work, we use the MIKE 21 SW spectral wave model developed at the Danish Hydraulic Institute (DHI, 2007). The model reproduces the main physical mechanisms of generation, transformation, and decay of wind waves. A description of the model and stages of its verification are described in detail in Divinsky and Kosyan (2017). Here, we present only the main features of the model:

- irregular grid for calculations covers the entire Black Sea basin; it consists of 20,000 elements of calculation (Fig. 1);
- the model uses the data of the global atmospheric reanalysis ERA-Interim as the initial wave field; the data are presented by the European Centre for Medium-Range Weather Forecasts (http://apps.ecmwf.int). The domain is limited by coordinates 40°N and 47°N, 27°E and 42°E. The spatial resolution of wind fields is the same by latitude and longitude, it is equal to 0.25°, the time step is 3 h.

We used the experimental data measured using various devices (Datawell buoys, ADCP, string wave recorders, satellite observations) to verify the model. The problem of surface waves separation into components requires initial experimental data that make possible calculation of frequency-directional spectra. The authors possess initial data of the wave experiment near Gelendzhik in 1996—2003 obtained using the Datawell Waverider instrument (Kos'yan et al., 1998). The coordinates of its location are: 44°30′40N, 37°58′70E (Fig. 1); the depth of the sea at the location is 85 m.

2.2. Separation of wave components based on experimental data

Two-dimensional spectrum of wind waves gives us a possibility to study the peculiarities of the wave energy distribution

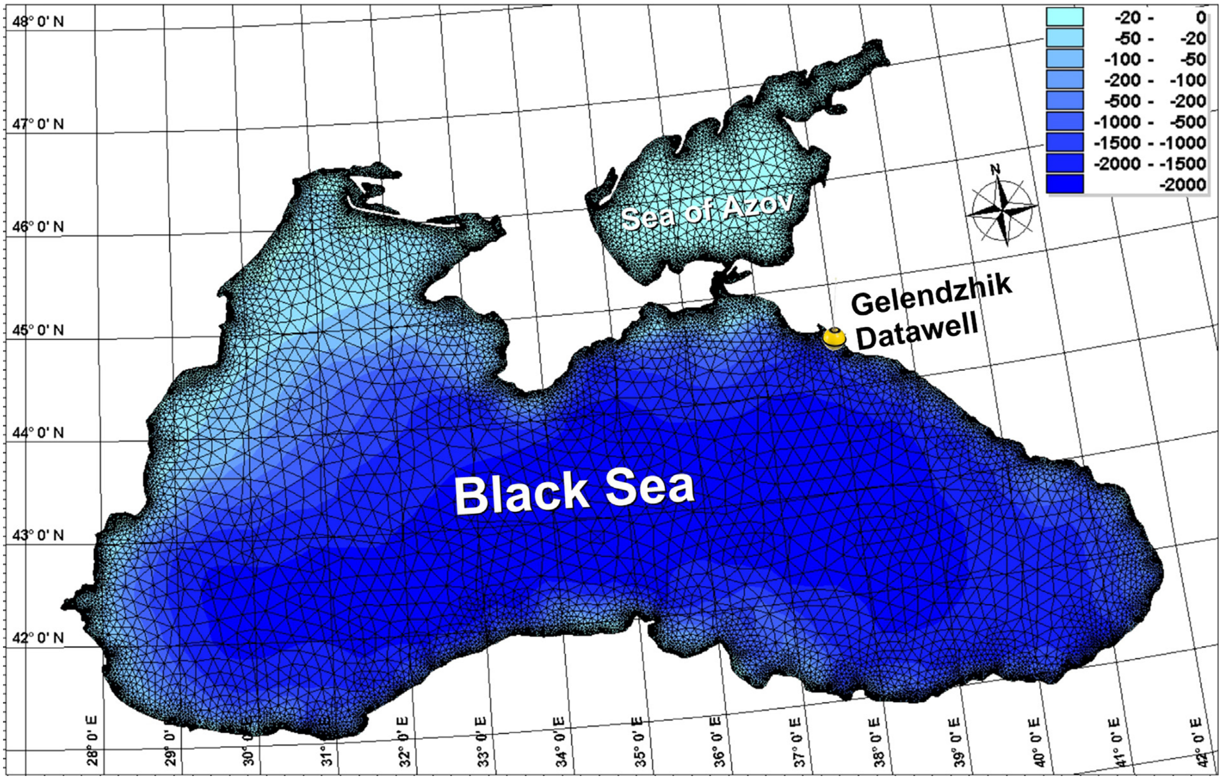

Figure 1 Calculation grid and bathymetric chart of the Black and Azov Sea (m).

both in the frequency range and by the direction of waves; hence it is possible to distinguish the wave systems.

We emphasize several important issues:

- location of the peaks of two-dimensional spectral density relative to the direction of the dominating wind is the determining issue of the analysis;
- when the atmospheric conditions change, the frequency-directional spectrum may contain several swell systems (in addition to the wind sea components). We do not put forward a goal of detailed description, thus, the concept of swell includes the entire surface waves whose direction does not match the general wind direction;
- the frequency maximum of the spectral density corresponding to swell is greater than the peaks frequencies of wind seas.

An example of separation of wind sea components and swell based on the analysis of two-dimensional experimental spectrum is shown in Fig. 2.

In this example, the frequency for separating the wave components is 0.16 Hz. Significant wave heights are found by integration of the corresponding intervals of two-dimensional spectrum $F(f,\Theta)$:

$$H_{s,swell} = 4\sqrt{\int_{f_l}^{f_{sep}} \int_0^{2\pi} F(f,\Theta) df d\Theta},$$

$$H_{s,wind} = 4\sqrt{\int_{f_{sep}}^{f_u} \int_0^{2\pi} F(f,\Theta) df d\Theta}.$$

Under the conditions of the change in the wind direction, the main part of the power spectrum belongs to the wind seas propagating from the south with a significant wave height of 1.42 m. The swell with a significant wave height of 1.11 m conserved its western direction. Integration of the entire spectrum results in the significant wave height of mixed waves equal to 1.80 m.

Fig. 3 gives an idea about the transformation of the two-dimensional spectrum during the propagation of an atmospheric cyclone and a sharp change in the wind direction. Under such conditions, the prevailing wind seas change to the domination of swell.

It follows from Fig. 3 that after the change in the wind direction from the southwestern to the northern, the resulting wave field consists of two swell systems (south-southeastern and western-southwestern) and northern wind seas. The estimates of significant wave heights of individual wave systems obtained by integration of the frequency-directional spectra are also shown in Fig. 3.

If we apply a similar procedure to the two-dimensional experimental spectra we can get the integral parameters of wind seas and swell over the time period we are interested in. The power spectra are calculated from 20-min time series that recorded the displacement of the buoys along three coordinates with a frequency of 1.28 Hz. The records in the experiment were collected with an interval of 3 h. When the significant wave height exceeded a threshold of 1.5 m, the records were registered every hour.

2.3. Tuning of the wave model

Spectral wave model MIKE 21 SW makes possible automatic separation of the model field of wind waves into individual components. The quality and physical background of this separation depend on the parameters specified by the user. We emphasize several important issues.

The MIKE 21 SW model is based on the solution of the equation of wave energy balance. The main physical processes (wind pumping, wave breaking, energy dissipation caused by bottom friction and wave breaking) are described with semi-empirical functions. We assume that in the conditions of our measurements the effects related to the bottom friction and wave breaking over shallow depths have a local character; therefore, the parameters describing these effects do not participate in the tuning of the model. The main calibration parameters are two coefficients, C_{dis} and δ_{dis}, which determine the numerical interpretation of the energy losses due to wave breaking (in other words, wave breaking over deep water):

- coefficient C_{dis} determines the general level of dissipation and, first of all, influences the wave heights;
- parameter δ_{dis} is an analog of the wave function; it controls the dissipation of individual components, thus influencing the wave periods. Variation of δ_{dis} from 0 to 1 allows us either to increase or decrease the dissipation level at low or high frequencies.

Strictly saying, it is not possible to interpret both coefficients independently: for example, the choice of coefficient

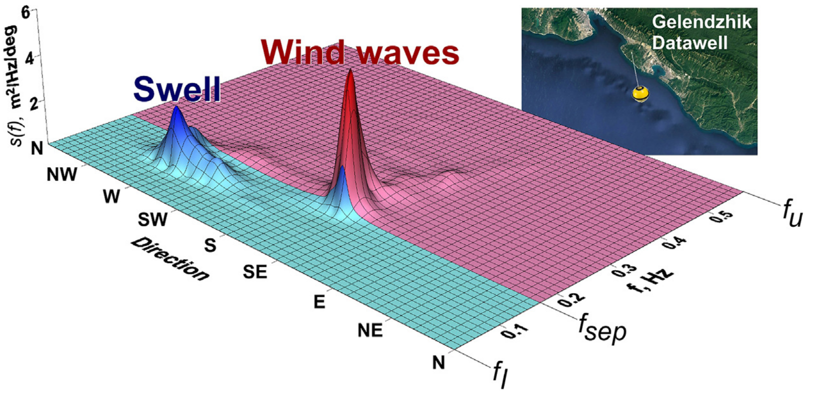

Figure 2 Separation of the components of wind waves (December 21, 1997; 20:00).

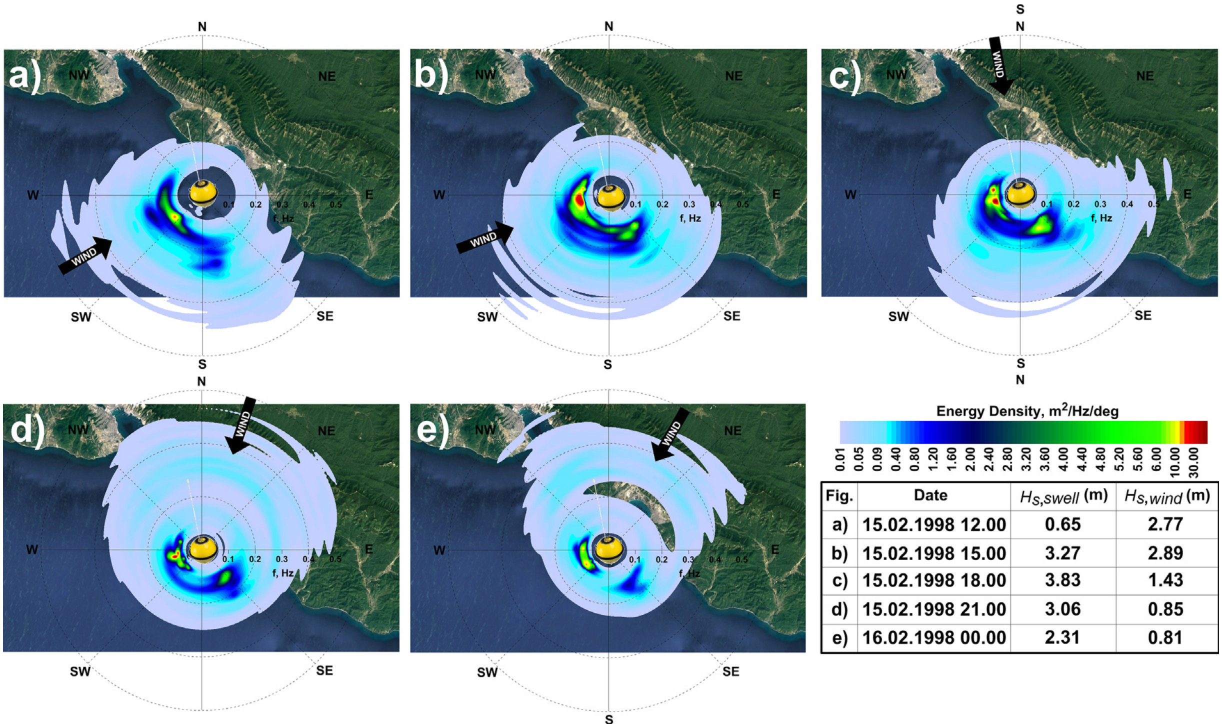

Fig.	Date	$H_{s,swell}$ (m)	$H_{s,wind}$ (m)
a)	15.02.1998 12.00	0.65	2.77
b)	15.02.1998 15.00	3.27	2.89
c)	15.02.1998 18.00	3.83	1.43
d)	15.02.1998 21.00	3.06	0.85
e)	16.02.1998 00.00	2.31	0.81

Figure 3 Experimental frequency-directional spectra of surface waves and significant wave heights of the corresponding components of swell and wind seas.

C_{dis} depends on the specified value of δ_{dis}. In addition, the optimum tuning of parameters C_{dis} and δ_{dis} is strongly determined by the physical conditions of generation and propagation of surface waves (Christie et al., 2014; Siadatmousavi et al., 2011).

We think that correct tuning of the spectral model under the conditions of automatic separation of the model field into individual components should provide the following:

- consistency between the model and experimental integral characteristic and the two-dimensional wave energy spectra both for the entire wave field and its components (swell and wind seas);
- physically justified statistical estimates of the parameters of swell and wind seas.

The numerical experiments allowed us to determine the optimum configuration of the spectral model:

- fifty spectral frequencies are distributed in the range of periods from 1.6 to 17.3 s based on the relation $f_n = f_0 C^n$ (f_0 = 0.055 Hz, C = 1.05, n = 1,2, . . . 50);
- the amount of discrete directions is 32 so that the model resolution with respect to the directions is 11.25°;
- the values of coefficients determining energy dissipation due to wave breaking are: C_{dis} = 5.5, δ_{dis} = 0.15;
- separation of wave components is performed using the criterion of wave age.

We give an example of the results of automatic separation of surface wave components in December 1997 (Fig. 4).

It follows from Fig. 4 that the spectral model quite reliably separates the components of swell and wind seas. A limited number of experimental time periods, for which we performed separation, is related to the fact that one of the goals of this research is a demonstration of the capabilities of the DHI spectral model to separate the components. We did not use the existing algorithms for separation of experimental spectra, which are applied to large datasets because the approaches to identify the spectral peaks realized in these approaches (relative heights, distances between peaks etc.) are not universal and require verification. Selected analysis of two-dimensional experimental spectra was performed manually with the account for wind characteristics.

Let us consider modeling results in more detail (Fig. 5).

We clarify that total significant wave height in Fig. 5 is determined as $\sqrt{H^2_{s,swell} + H^2_{s,wind}}$. The atmospheric circulation over the time period February 19—21, 1998 changed strongly several times. The conditions of swell formation were different. On February 15—16, a change of the strong southwestern wind to the northeastern direction caused generation of swell with significant wave heights comparable with the heights of wind seas (the transformation of experimental two-dimensional spectrum is shown in Fig. 3). There was no strong wind change on February 17—18; therefore, the waves from the east dominated in the storm conditions. On February 19—20, the stably directed southwestern wind gradually increased and decreased. This change generally did not cause the development of swell. The calculated two-dimensional wave energy spectra for the selected time periods on February 15—16 are shown in Fig. 6.

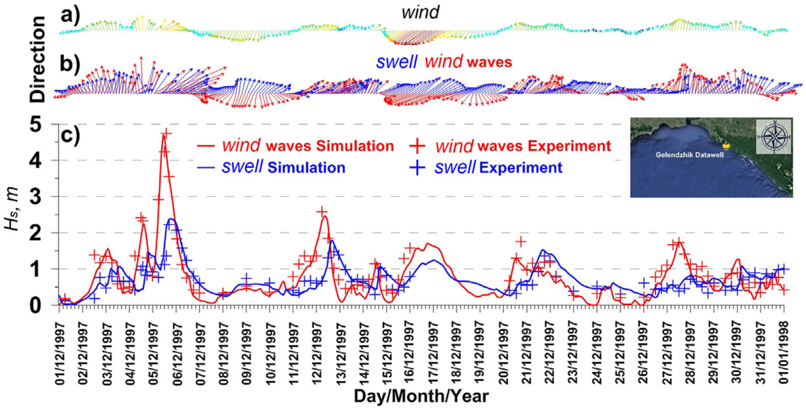

Figure 4 Comparison of the model and experimental parameters of surface wave components in December 1997 at the location of buoy Gelendzhik Datawell. (a) General direction of the wind; (b) mean direction of the swell (blue vectors) and wind seas (red vectors); (c) simulated and experimental significant wave heights of wave components.

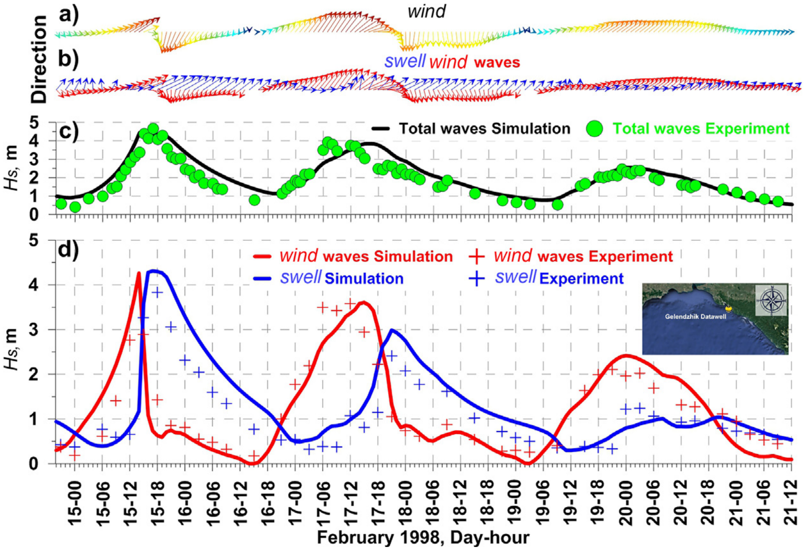

Figure 5 Comparison of the model and experimental parameters of surface waves on February 15—21, 1998 at the location of buoy Gelendzhik Datawell. (a) General direction of the wind; (b) mean direction of the swell (blue vectors) and wind seas (red vectors); (c) simulated and experimental total significant wave heights; (d) simulated and experiments significant wave heights of wave components.

It follows from Fig. 6 that model spectra adequately reflect the physical mechanism of the development of wind seas related to the sharp change in the wind direction. They generally correspond to the experimental spectra during the same time period (Fig. 3). Some distortions are related to the localization of secondary southwestern swell.

Fig. 7 shows the histograms of surface wave parameters in the winter period from December 1, 1997 to March 31, 1998. Here: (a)—(c) are model data with separated wave components; (d)—(f) are modeling results related to the total wave field.

Let us summarize the results shown in Fig. 7:

- significant swell heights (Fig. 7a) are on the average 0.5—1.0 m; the distribution of swell periods has two peaks (Fig. 7b); the peaks correspond to periods of 4 and 7 s; the direction of swell (Fig. 7c) is limited by sector 170—270°;
- the spectral model generally correctly reproduces the main statistical properties of the total wave field including significant wave heights (Fig. 7d) and mean periods (Fig. 7e);
- the recurrence frequency of the southwestern wave direction exceeds the other directions (Fig. 7f). This is caused by the underestimation of the northeastern winds. Strong northeastern winds (katabatic winds, bora) are characteristic of the coastal zone studied here. These winds are not adequately represented by the ERA-Interim global reanalysis.

2.4. Brief notes and conclusions

Thus, we performed tuning of the spectral model, which adequately separates the wave field into individual

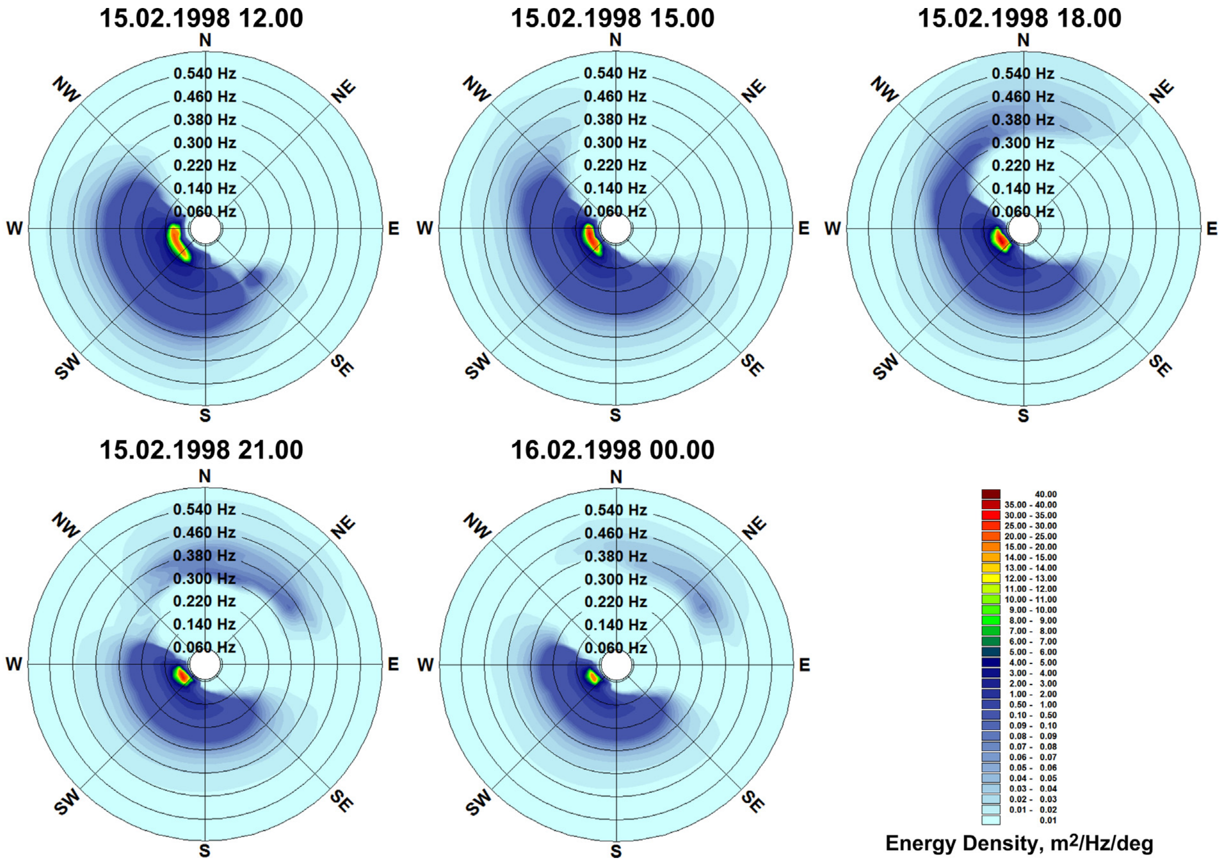

Figure 6 Model frequency-directional spectra of surface waves on February 15—18, 1998.

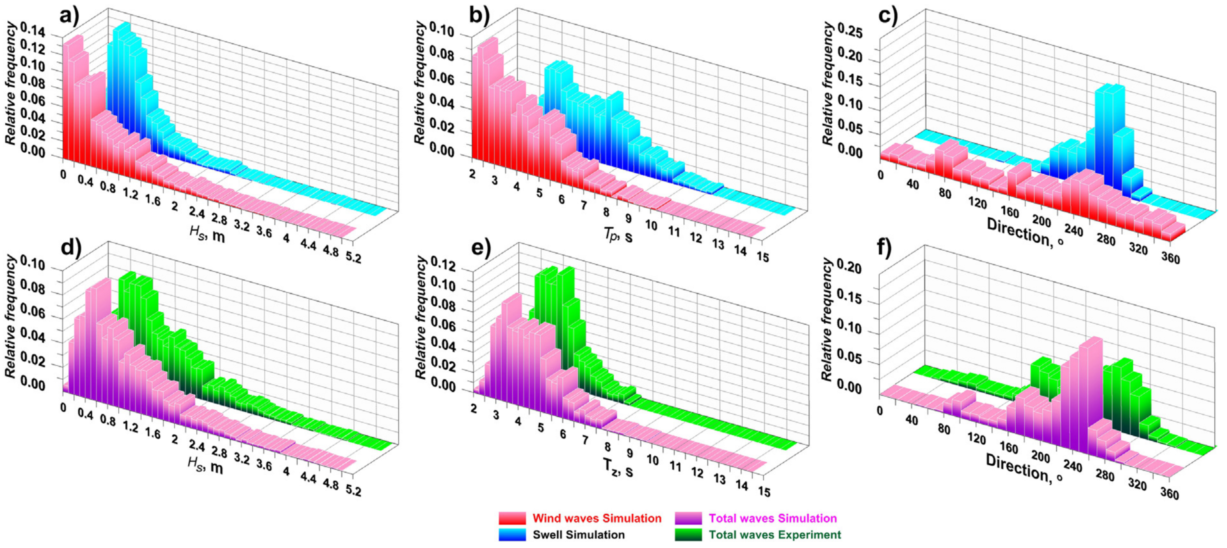

Figure 7 Statistical distribution of parameters of wind waves from December 1, 1997 to March 31, 1998 (a)—(c) show wave components; (d)—(f) show total wave field.

components. The model frequency-directional wave spectra generally correspond to the two-dimensional experimental spectra. Statistical peculiarities of integral parameters of swell and wind seas are physically justified (Fig. 7). Overestimation of the swell contribution to the total wave field under the conditions of sharp wind change is a disadvantage of the model.

We emphasize an important fact. The tuning parameters used in the description of wave energy dissipation due to white-capping were obtained from the analysis of the experimental data in the northeastern part of the Black Sea. It is difficult to say whether they are valid for the entire sea basin. Weak coverage of the Black Sea with experimental wave stations, which make possible to get the main wave characteristic: two-dimensional wave energy spectra, is an obstacle to solve this problem. We understand the role of these restrictions and will make an attempt to estimate in the first approximation the peculiarities of the propagation of surface wave components in the Black Sea.

3. Results and discussion

We constructed a dataset consisting of the fields of calculated parameters of wind wave components in the Black Sea with a time step of 1 h, which covers a period of 10 years (2007—2016). The dataset of calculated characteristics includes the following (separately for swell, wind seas, and total wave field):

- spatial distributions of significant and maximum wave heights, mean periods, periods of spectral maximum, wave directions;
- frequency-directional spectra;
- power of waves.

The power of irregular wind waves can be determined as a function of the squared significant wave heights and energetic period (Boyle, 2004). The unit of measurements is kilowatt per meter of the wave front. Estimates of wind wave power completely depend on the correctness and adequacy of the spectral model during reproduction of all stages of wave development. Let us discuss the wind wave power because power is a function of two main integral parameters of wind waves (height and period); thus, it characterizes the energetic importance of storms.

Figs. 8 and 9 present spatial distribution of mean power of wind seas and swell over a period from 2007 to 2016. Averaging was performed over a rectangular grid with sides 12.5 × 11.5 km.

The maximum power of wind seas is recorded in the western part of the sea, which results in a clearly manifested maximum of the spatial distribution (Fig. 8). The region of high wave power spreads in the meridional direction from west to east turning around Crimea. The mean power of swell is distributed more uniformly (Fig. 9). The local power peaks are observed in the southwestern and southern parts of the Black Sea. In general, the swell is spread everywhere excluding shallow bays in the northern part of the sea.

Let us estimate the contribution of swell to the total power of surface waves. With this in mind, we plot a chart of the ratio of swell power P_{swell} to the power of the total wave field P_{total}, $(P_{swell}/P_{total}) \times 100\%$, Fig. 10.

Fig. 10 clearly demonstrates the domination of contribution of wind seas to the total power of wind waves in the Black Sea ($P_{swell}/P_{total} < 0.5$). Swell dominates in the shelf zone of the southern and eastern parts of the sea. The wave climate in the narrow coastal zone of these regions is almost completely determined by the swell fields ($P_{swell}/P_{total} > 0.8$). The recurrence of swell by directions has its specific peculiarities in different regions of the sea (Fig. 11).

Swell from the western-northwestern direction dominates in the deep-water part of the Black Sea. The southwestern and central regions of the sea are influenced by the swell from the northeast. Swell from the southeast is manifested in the northwestern part, while the southwestern swell dominates in the northeastern part of the sea. The strongest swell with a power exceeding 20 kW m^{-1} develops in the southeastern, northeastern, and southwestern regions of the sea.

It was discussed above that climatic estimates of the distribution of surface wave components were summarized over a period of 10 years (2007—2016). These estimates need much computational resources. We hope that further research would allow us to widen the database of wave parameters and clarify the results presented here.

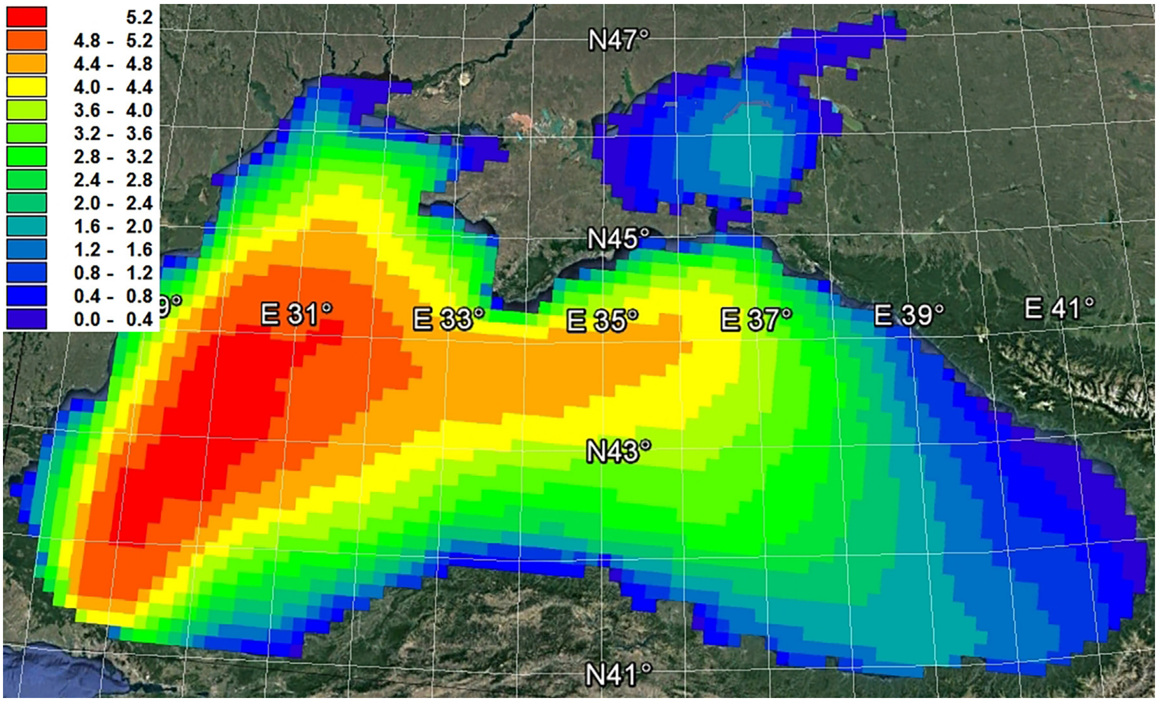

Figure 8 Mean power of wind seas over 2007—2016 (kW m^{-1}).

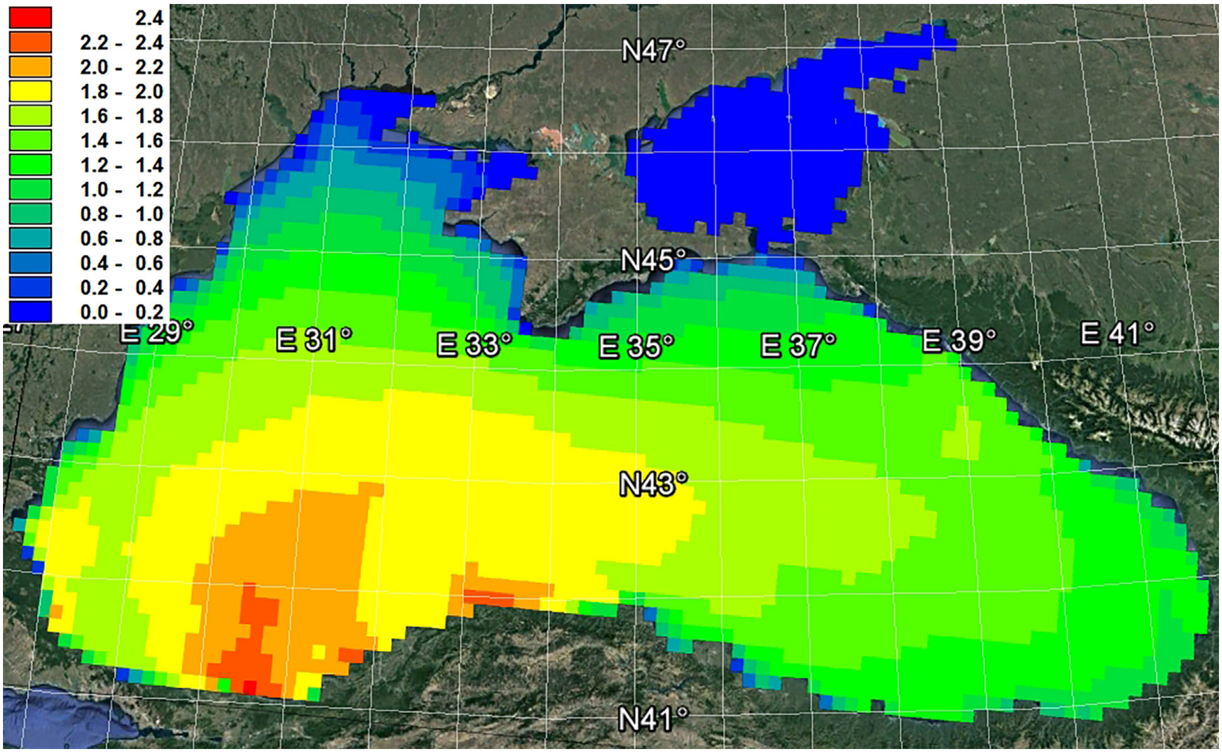

Figure 9 Mean swell power over 2007—2016 (kW m^{-1}).

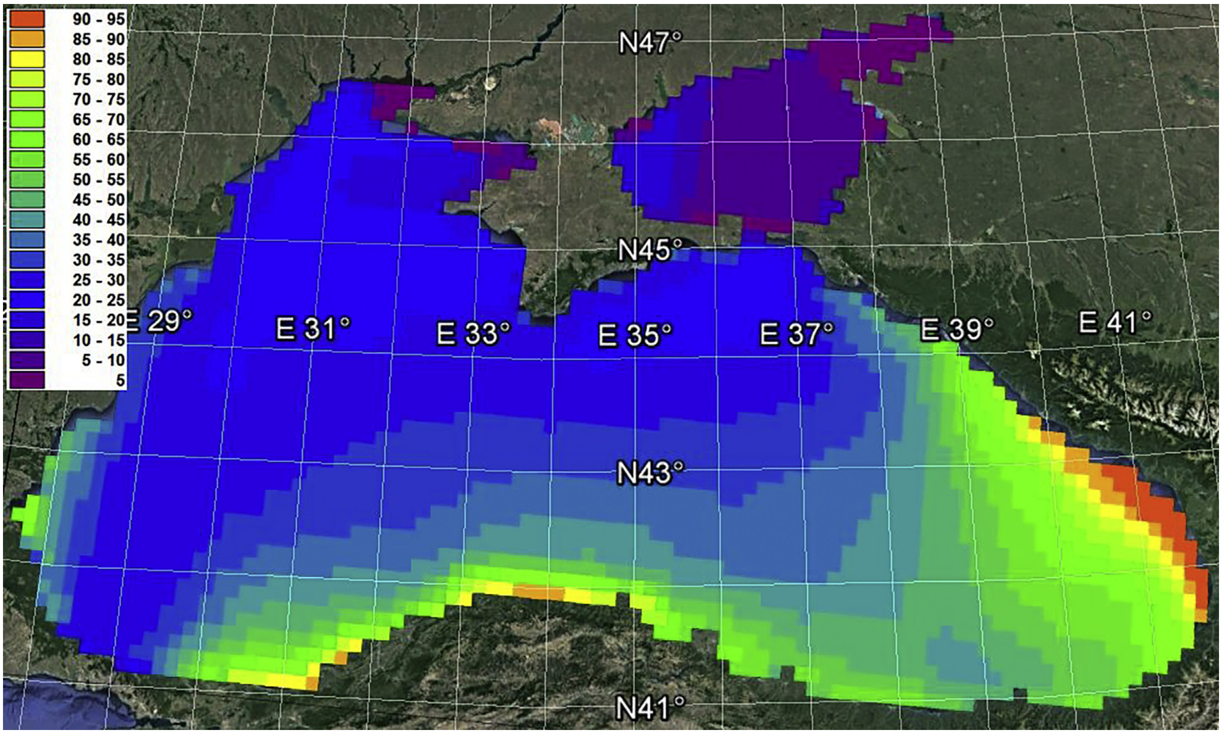

Figure 10 Ratio of the mean swell power to the power of the total wave field in 2007—2016 (%).

4. Conclusions

The main goal of the study presented here is an assessment of climatic peculiarities in the distribution of wind seas and swell in the Black Sea. The analysis is based on numerical modeling using the DHI MIKE 21 SW spectral wave model. Previously, the model was verified on the basis of numerous instrumental observations of wind waves in the Black and Azov Sea.

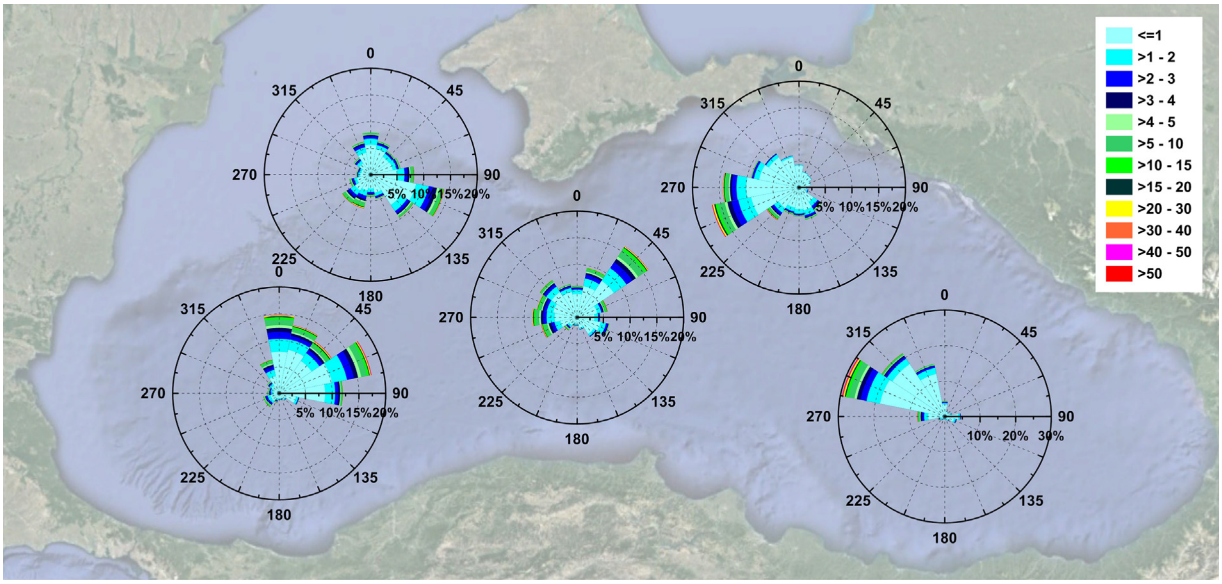

Figure 11 Rose graphs of swell power (kW m^{-1}) in the Black Sea in 2007—2016.

The main results of our research are as follows:

- we studied the peculiarities of the spatial distribution of wind sea and swell power in the Black Sea over the last 10 years (2007—2016);
- we determined the regions, in which wind seas and swell dominate on the basis of their contribution to the total wave field of mixed waves;
- auxiliary numerical experiments allowed us to determine the optimal tuning and adjustments of the spectral wave model for automatic separation of wave components;
- the model correctly reproduces the main integral characteristics of mixed wave;
- the model frequency-directional wave spectra generally correspond to the experimental two-dimensional spectra;
- statistical peculiarities of integral parameters of swell and wind seas are physically justified.

We emphasize some important details. Two coefficients C_{dis} and δ_{dis}, which determine the numerical interpretation of the energy losses due to wave overturning, are the main calibration parameters of the MIKE SW model in the problem of automatic separation of wave components. The values of these coefficients were determined at the stage of the model verification using the experimental wave data in the north-eastern part of the Black Sea. Of course, without the corresponding experimental verification we cannot consider that these coefficients are universal for the entire basin. Insufficient coverage of the Black Sea with the direct instrumental observations is a problem of any research. Satellite altimetry provides mean data and cannot be used as the basis of the special analysis. These restrictions are the natural disadvantages of our investigations.

The last comment. The existing methods of separating the components of sea waves are based not on the experimental data but on the materials from the global wave models (WAM, WAVEWATCH). It is clear that the global models do not reflect the specific regional features of waves. Hence, the errors in the estimates of two-dimensional model spectra are added to the indefiniteness, which is characteristic of the separation of wind seas and swell. In other words, we think that analysis of the consistency between the two-dimensional model and experimental spectra should become one of the initial stages of the investigation, which would later make possible to get correct wave statistics.

Acknowledgments

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