Oceanologia (2020) 62, 23—30

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ORIGINAL RESEARCH ARTICLE

Extreme wind waves in the Black Sea

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Received 9 January 2019; accepted 28 June 2019
Available online 7 December 2019

KEYWORDS
Wind waves;
Swell;
Wave climate;
Black Sea;
Numerical modeling;
Return period

Summary Results of the analysis of a long-term data set, including fields of significant wave heights of the surface wave components, and mixed (total) wave field in the Black Sea are presented. The data set was collected on the basis of retrospective calculations using the MIKE 21 SW spectral wave model with the atmospheric forcing based on the ERA-Interim data in the period from 1979 to 2017. A criterion is used to isolate the swell waves from the initial wave data set that takes into account the wave age. We used the experimental data to develop a regression relationship showing that the maximum possible wave height can exceed the significant wave height approximately one and a half times. Analysis of the spatial distribution of wave heights in the Black Sea suggests that a possibility exists that significant wave height of storm waves can be as high as ~12 m. This result indicates that the actual heights of maximum waves in the Black Sea can reach 18—19 m. Three regions are distinguished on the basis of the wave potential. The times of manifestation of extreme situations in these regions are different: in the southwestern part of the sea, extreme storm situations occur, as a rule, in December—January; in the region south of the Crimea Peninsula this happens in February; in the northeastern part of the sea they occur in November. It was also found that the south-southeastern and eastern parts of the sea are most affected by swell.

1. Introduction

Application of sea transport routes, hydraulic engineering construction, planning and production of offshore works, study of hydrodynamic processes and the structure of sea water require information about the regimes of wind waves. Climatic characteristics of wind waves can be divided into two parts: operational, reflecting events of frequent recurrence, and extreme, possible once in a given number of years. The greatest interest is the study of the destructive

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Peer review under the responsibility of Institute of Oceanology of the Polish Academy of Sciences.

Production and hosting by Elsevier

https://doi.org/10.1016/j.oceano.2019.06.003

extreme waves. A simple question is put forward: what maximum waves are generally possible in the Black Sea?

The first publications about this problem were apparently the works of Matushevsky (1978, 1979). The author provides an estimate of the height of maximum waves based on the analysis of the regime functions of the distribution of wave heights, possible once every 50 years; their height is 14.4 m. According to Matushevsky, the maximum ever possible wave height in the Black Sea is 15.0 m.

Unfortunately, verification of such assessments is restricted by a strong lack of experimental data. However, we can cite several examples of successful experiments on recording wind wave parameters in the offshore zone. In 1996—2003 wave characteristics were measured on the northeastern shelf of the sea near the city of Gelendzhik using a Datawell Waverider wave recorder (Kos'yan et al., 1998). The maximum recorded wave height in the entire experiment was 12.43 m (over the 80 m depth of the sea). In the northwestern part of the sea, a significant wave height of 11 m was recorded on the Gloria platform using a string wave recorder (Rusu et al., 2006). Since this height (11 m) is presented in the widely accepted common terms of significant wave heights let us find the relationship between the significant and maximum wave heights. We possess about 14 thousand 20-min records of the displacements of the Datawell Waverider buoy in the horizontal and vertical planes. Each record contains wave profiles at the intersection of the zero surface, and we can determine the maximum wave height in each record; then, we construct the frequency spectrum and find the significant wave height. Regression of significant and maximum wave heights based on the experimental data is shown in Fig. 1.

Fig. 1 also contains a box-whisker plot, describing statistics of the ratio of maximum wave heights to significant heights (location of the average value of the ratio and also the values of 10, 25, 75, and 90% distribution quantiles). It follows from Fig. 1, that the maximum wave heights exceed the significant waves approximately by a factor of 1.54. Returning to the observations on the Gloria platform, we state that if the significant wave height is 11 m as reported in Rusu et al. (2006), the maximum wave height should be as high as about 17 m.

Instrumental measurements of wind wave parameters in the open part of the Black Sea (in the context of the possibility of using them for climate analysis) are almost absent. Among the available observation tools, we distinguish visual assessments (from the passing ships), satellite altimetry, and numerical simulation. The visual method of determining the characteristics of waves is associated with significant subjectivity. Satellite observations are characterized by obvious advantages (unchanging tracks, in particular), and by the disadvantages of uncertainties in the interpretation of signals. Mathematical modeling for studying wind waves is a modern method, which in some sense has no alternative. The spectral wave models of the last generation fully describe the physical nature of generation, transformation, and decay of the surface waves. Since we are interested in the manifestation of extreme waves in the Black Sea, we cite several works devoted to this approach. In the publication by Rusu (2016), the author describes the constructed predictive wave system based on the SWAN model, and provides some results of the calculation of wind-wave fields. We cite the author: "*... there are areas in the sea where the significant wave height is greater than 10 m, which means*

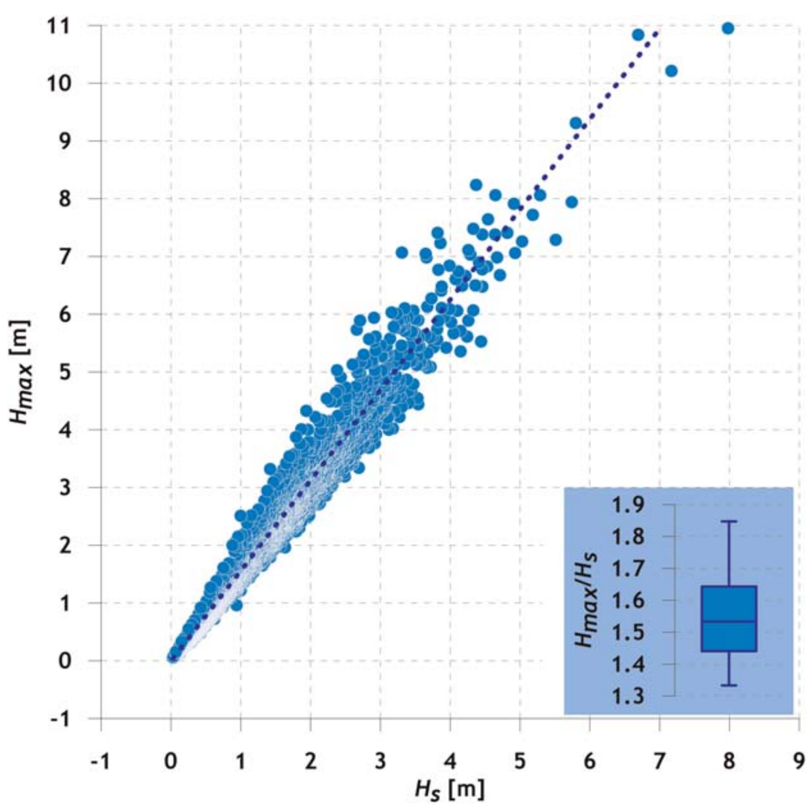

Figure 1 Relation between the significant and maximum wave heights based on experimental data.

that we may expect maximum wave heights of about 20 m, or even greater". In the paper by Polonsky et al. (2011), the authors estimate the characteristics of the wave fields of the Black Sea in 1979—2008. They show that waves with the maximum heights of significant waves exceeding 12 m are possible. The region of occurrence of such waves is the southwestern part of the sea.

We also note two works (Akpınar et al., 2016; Van Vledder and Akpinar, 2016). In the first article spatial maps of the maximum wave heights in the period from 1979 to 2009 were constructed, with the wave heights for wind seas limited to 8 m, which seems to be underestimated. In the second article, over the same period, the distributions of the maximum significant wave heights in the Black Sea area were obtained. The areas in which the magnitudes of significant wave heights reach maximum values are identified: southwest (9.7 m), east (9.5 m) and in the region of the Crimean peninsula (8.3 m).

Thus, the question of maximum waves in the Black Sea is still pressing. In this relation, in the work suggested here: (1) we study the space-time properties of the manifestation of the maximum waves over a climatic time period; (2) we analyze wave heights possible once in a given number of years. Studies have been carried out both for the wave field components (pure wind waves and swell) and total (mixed) waves.

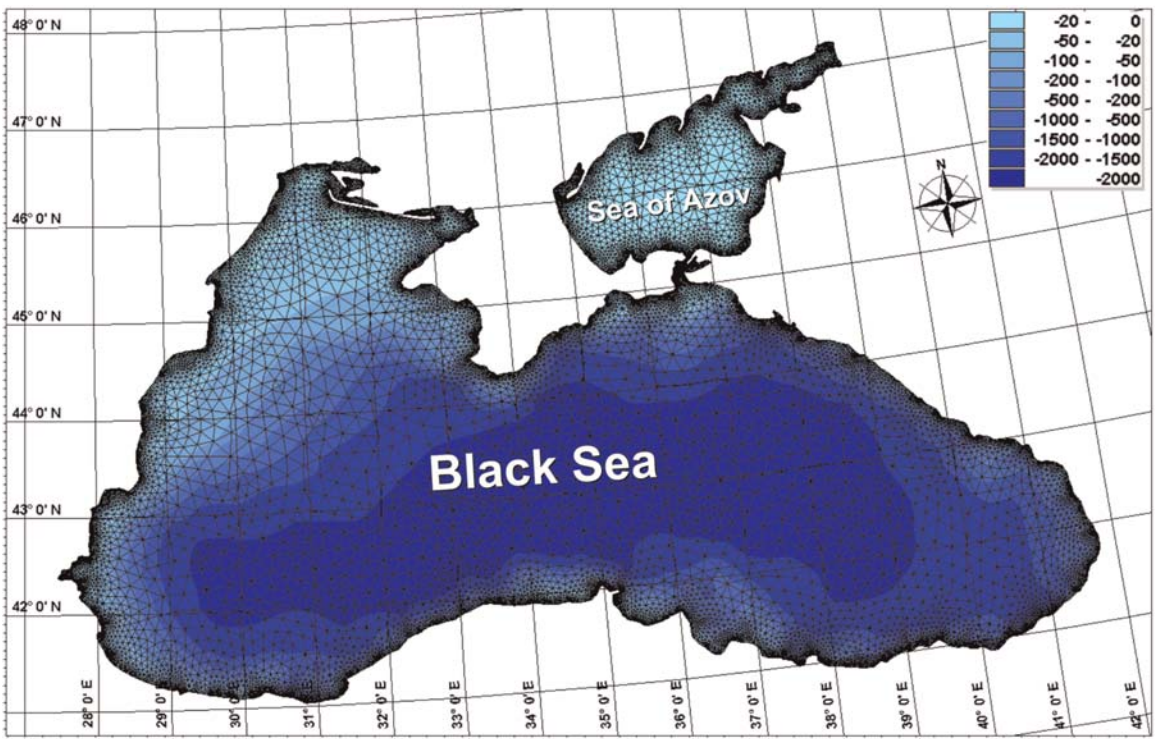

Figure 2 Grid for calculations and bathymetric chart of the Black and Azov seas.

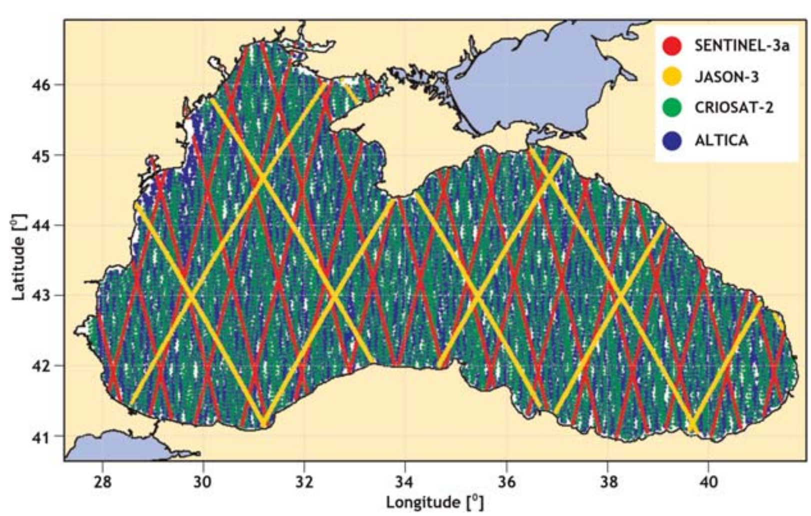

Figure 3 Distribution of satellite altimetry observations over the Black Sea from December 2017 to October.

2. Methods and approaches

2.1. Numerical model

In this work, we use the MIKE 21 SW spectral wave model developed at the Danish Hydraulic Institute (DHI, 2007). A description of the model and stages of its verification as applied to the measurements in the Black Sea is presented in Divinsky and Kosyan (2017). Here, we note only the most important issues:

- the model realizes the main physical mechanisms of the generation, transformation, and decay of wind waves;
- irregular grid for computations covers the basins of the Black and Azov seas, it consists of 10 000 elements (Fig. 2);
- the ERA-Interim reanalysis data prepared by the European Centre for Medium-Range Weather Forecasts (http://apps.ecmwf.int) are used as the initial wind fields. The model domain is limited by coordinates: 40.5°N and 47.5°N by latitude, 27°E and 42°E by longitude. The spatial resolution by latitude and longitude is 0.25°; the time resolution is 3 h.

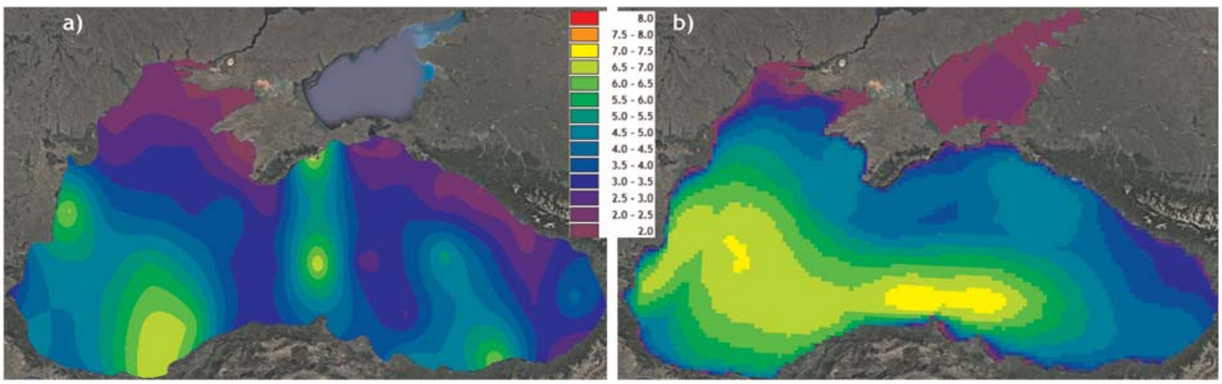

Figure 4 Maximum significant wave heights [m] in the Black Sea in the period from December 1, 2017 to September 30, 2018. (a) Generalization of satellite data; (b) modeling results.

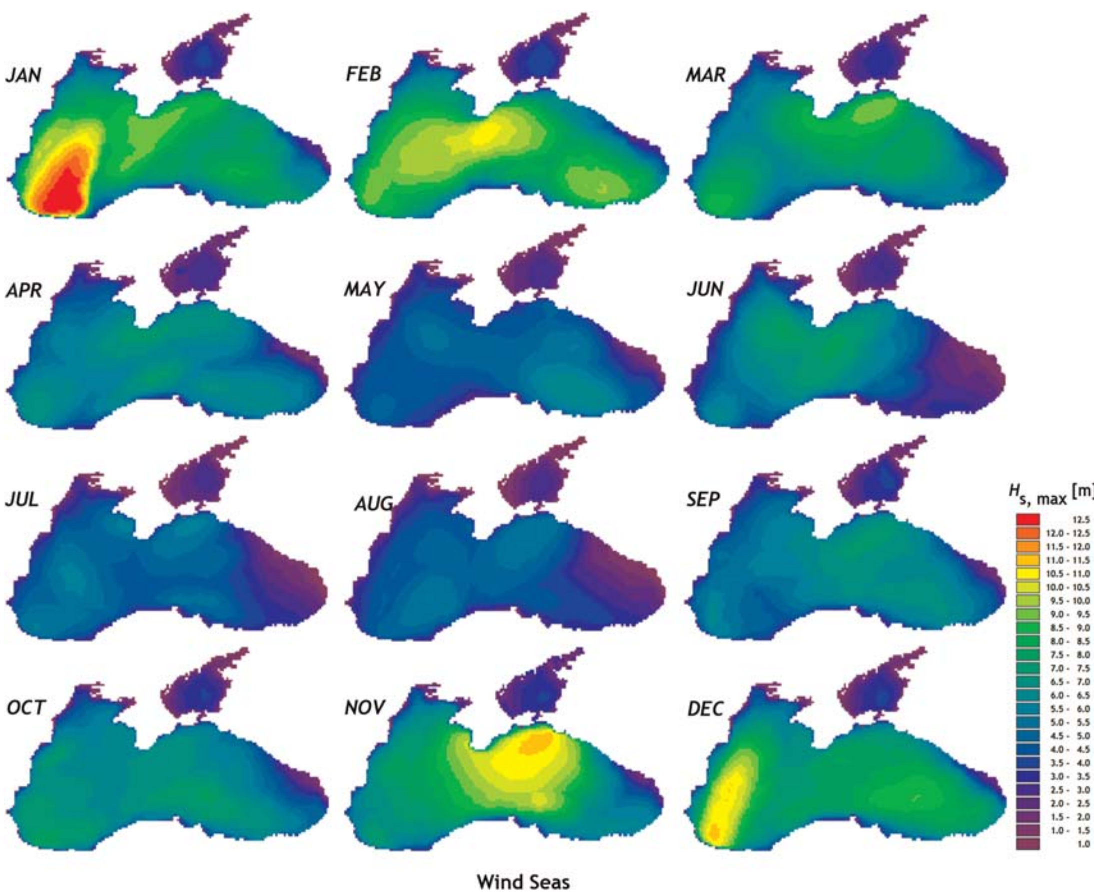

Figure 5 Wind waves. Maximum significant wave heights [m] over the Black Sea from 1979 to 2017.

We note that despite the fact that the grid covers the Azov Sea, the results in this sea are not completely representative without the account for the ice cover in the winter months; therefore, we do not discuss these results here.

Tuning of the DHI MIKE 21 SW spectral wave model for automatic separation of surface wave components is described in detail in Divinsky and Kosyan (2018). Here, we only give the parameters of optimum configuration of the spectral model:

- 50 spectral frequencies are distributed in the range of periods from 1.6 to 17.3 s using the following relation $f_n = f_0 C^n$ (f_0 = 0.055 Hz, C = 1.05, n = 1, 2, ..., 50);
- the number of discrete directions is 32; hence, the directional resolution of the model is 11.25°;
- the coefficients determining energy dissipation caused by wave breaking are: $C_{dis} = 5.5$, $\delta_{dis} = 0.15$;
- separation of wave components is performed using the criterion that takes into account the wave age. The wave component corresponds to swell if the following condition is satisfied $\frac{U_{10}}{c}\cos(\theta - \theta_w) < 0.83$, where U_{10} is wind speed; c is phase velocity of waves; θ, θ_w are the directions of waves and wind, respectively.

As a result of calculations, we prepared a data set of spatial fields of parameters of wind waves, swell, and mixed waves for the period from January 1979 to December 2017 with a time step of one hour. Fields of significant wave heights were used for further analysis.

Since we are analyzing spatial maps, we note the following important issues related to the possibility of using satellite data. A clear advantage of the results of altimetric measurements is the possibility of their spatial generalization. In 2018, the EU Copernicus Marine Service (http://marine.copernicus.eu) developed a new product that includes the results of restoring the height of significant waves from the data of several satellites starting from July 2017. As an example, we take the time interval from December 1, 2017 to September 30, 2018. The spatial distribution of the tracks of the Saral/Altica, Criosat-2, Jason-3, and Sentinel-3a satellites in the specified period is shown in Fig. 3.

The spatial resolution of the data is approximately 7 km. This is the best satellite altimetry configuration, providing the most reliable results. The maximum wave heights were determined in the spatial cells with sizes of 0.1 × 0.1, 0.25 × 0.25, 0.5 × 0.5, and 1 × 1 degrees. When the spatial cell size is 0.1 × 0.1 degrees, from 1 to 20 measurements per year generally fall into each cell; and from 1000 to 3000 measurements per year appear in the spatial cell sizes of 1 × 1 degrees. The largest number of measurements appear in the cells through which the tracks of the Jason-3 and Sentinel-3a satellites pass, since they have strictly repeated orbits with periods of 10 and 27 days. This factor precisely determines the reliability of data on maximum wave heights.

Fig. 4 shows the spatial distributions of the maximum significant heights of mixed waves based on the analysis of

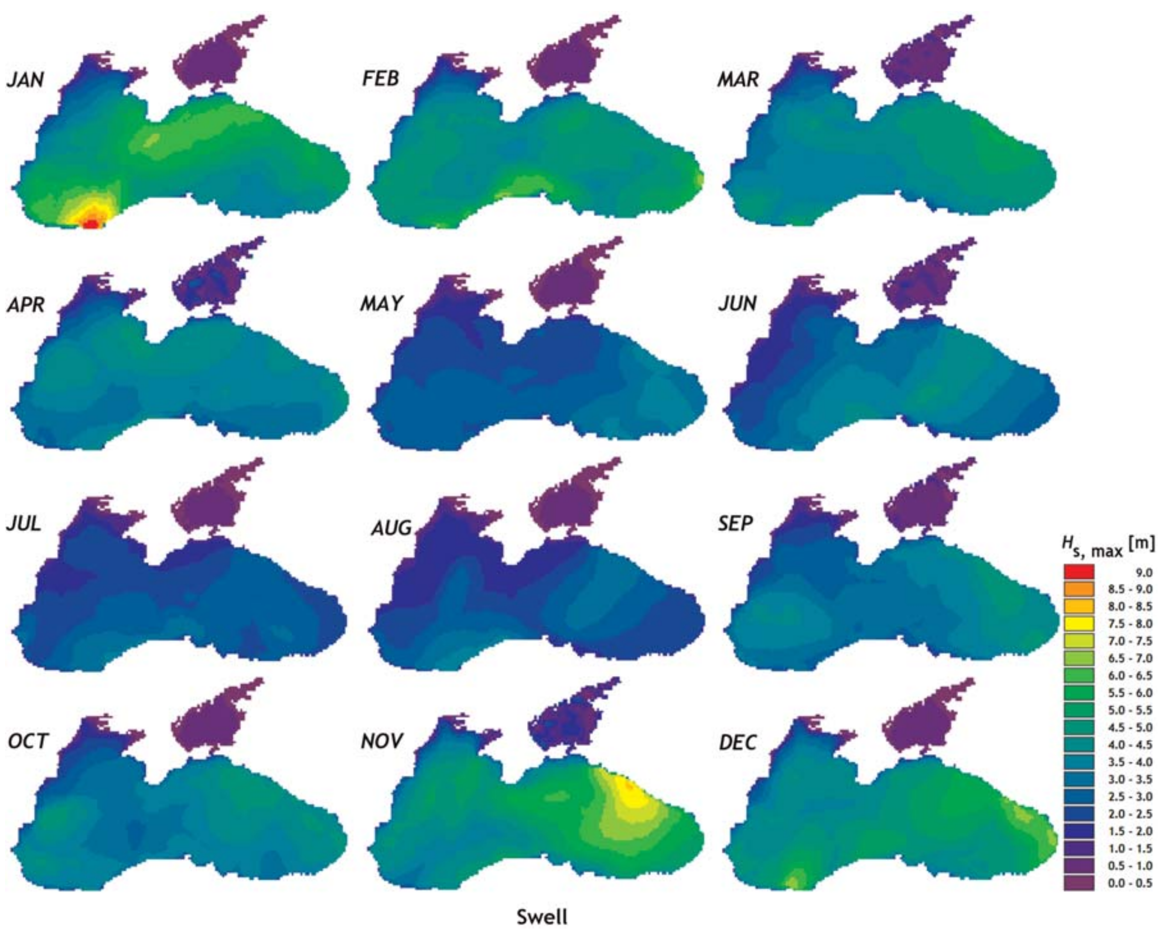

Figure 6 Swell. Maximum significant wave heights [m] over the Black Sea from 1979 to 2017.

satellite data (Fig. 4a) and calculated estimates using the spectral wave model (Fig. 4b).

It follows from Fig. 4 that there is no reason to talk about sufficient compliance of satellite and calculated fields, due to uneven coverage of the Black Sea area with satellite data in both space and time. As we mentioned above, the data of the Jason-3 and Sentinel-3a satellites are most representative, but unfortunately, the total coverage of the basin by these satellites is low. Nevertheless, let us point out some general properties of satellite and calculation charts: (1) both maps, in principle, reflect the fact that during the studied period of time stronger waves were observed in the southern part of the sea, compared to the northern part; (2) both maps give somewhat similar estimates of the maximum heights of significant waves. The latter fact provides some confidence in the correctness of tuning the main research tool: the spectral wave model.

2.2. Method of estimating extreme wave heights

The method of annual maxima, based on the Gumbel integral distribution function, was used to estimate the extreme heights of surface waves (Kamphuis, 2000; Lopatoukhin et al., 2000):

$$F(h) = \exp\left(-\exp\left(-\frac{h-\alpha}{\beta}\right)\right), \quad (1)$$

where $F(h)$ is the probability that wave height does not exceed h; and α and β are parameters determined for each specific point from the time series of annual maxima wave heights. Parameters α and β are determined for each node of the calculation grid using the least square method.

The following expression for wave height corresponding to the given value of quantile F follows from (1):

$$h = \alpha + \beta(-\ln(-\ln F)). \quad (2)$$

Taking (2) into account, the estimate of wave height possible once in T years is determined as quantile $(1 - 1/T)100\%$ of statistical reliability of distribution (1):

$$h_T = \alpha - \beta \ln\left(-\ln\left(1 - \frac{1}{T}\right)\right). \quad (3)$$

The field of significant wave heights possible once in a given number of years is a result of the above procedure.

3. Results and discussion

3.1. Maximum waves in the sea basin based on modeling

A data set has been formed, consisting of fields of calculated parameters of the components of wind waves, swell, and mixed waves in the Black Sea, covering a period of 39 years (from 1979 to 2017) with a time step of one hour. Figs. 5—7

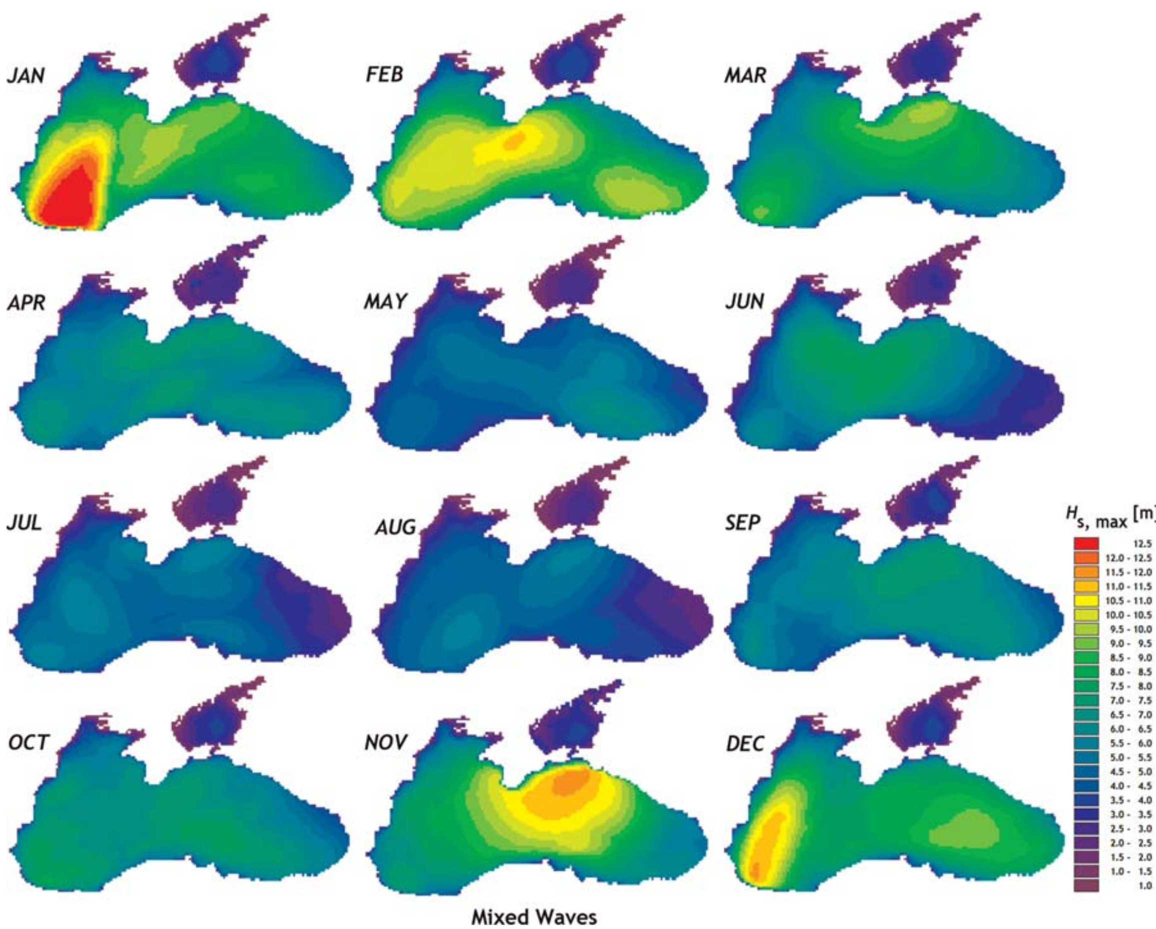

Figure 7 Mixed waves. Maximum significant wave heights [m] over the Black Sea from 1979 to 2017.

show the spatial distributions of the maximum significant heights of the components of surface waves, and total (mixed) waves.

We note that the wave dynamics of the Black Sea is generally determined by two processes: propagation of Atlantic cyclones over the Black Sea, resulting in strong waves in the northeastern part of the sea, and anticyclones with centers in Eastern Europe, causing waves in the southwestern regions of the sea.

These features are fully reflected in the maps of maximum wave heights (in our case, in the terms of significant as mentioned above). The strongest wind waves with heights exceeding 12 m appear in the southwestern part of the sea. The months with the strongest storms are January and December. In the northeastern part, waves may develop with altitudes of the order of 11 m; as a rule, this occurs in November. In February, the southern coast of the Crimea Peninsula appears in the zone of the greatest waves. In March, zones of dynamic activity are quite clearly pronounced (southwestern and northeastern parts of the sea), which is associated with the restructuring of the atmospheric systems between winter and summer

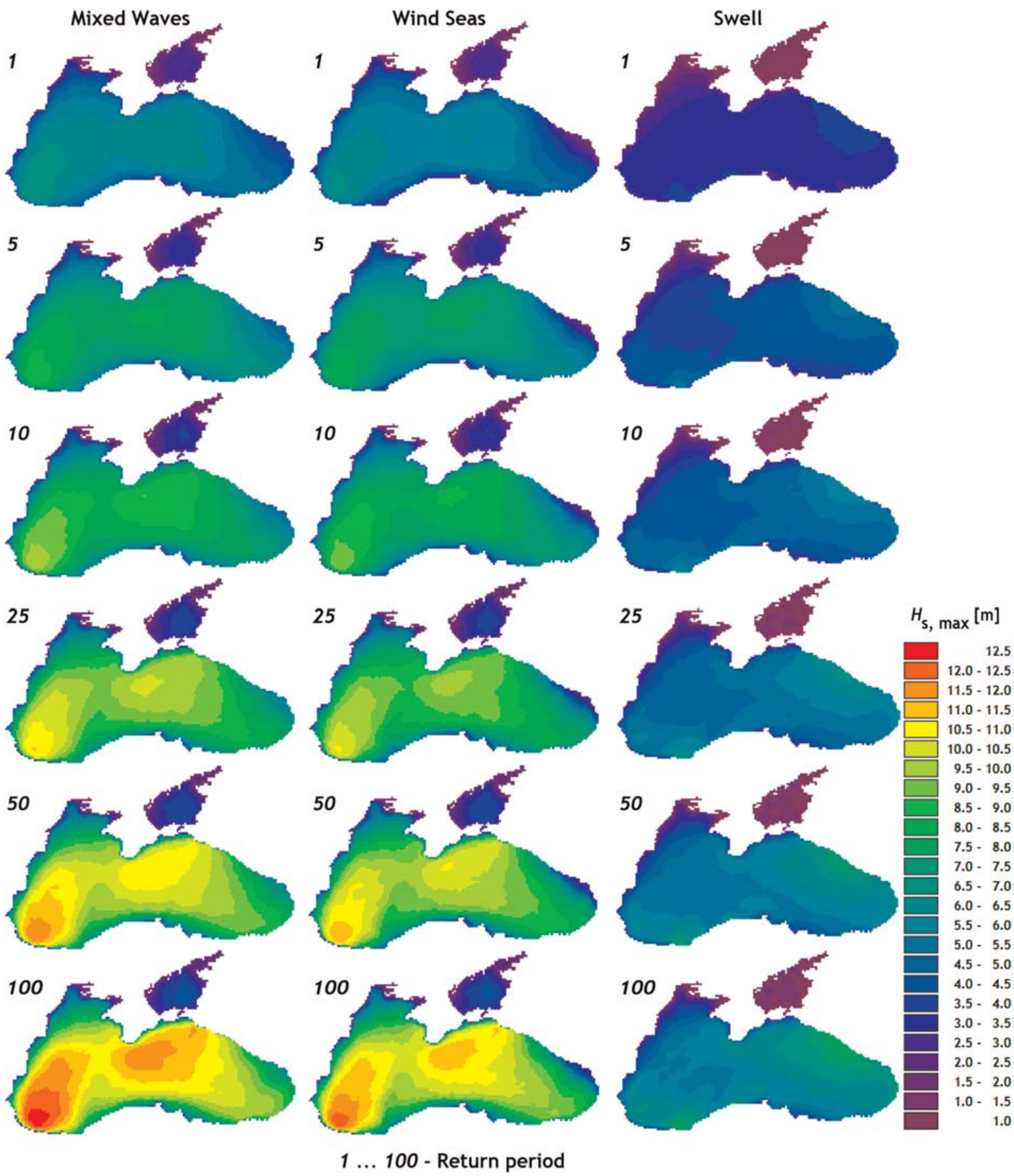

Figure 8 Maximum wave heights possible once in the given number of years.

types. July and August are the calmest months over the entire sea.

The distribution of maximum swell waves is, of course, different from the wind waves, since the swell propagates beyond the zones of surface wave generation. The main regions of maximum swell waves are in the south-southwestern and eastern parts of the sea. The height of the swell usually does not exceed 6—7 m. The 9-m swell recorded in January (Fig. 6) is a single case over the analyzed period of time; it is related to the catastrophic storm in 2004.

Spatial indicators of fields of mixed waves (Fig. 7) repeat, in general, the maps of wind waves, excluding the extreme eastern regions of the sea, in which swell prevails. The stormiest regions with wave heights of the order of 11—12 m are: the Bosporus region, the southern coast of Crimea, and the northern-northeastern part of the sea.

3.2. Wave heights of given recurrence

Let us estimate the spatial distribution of the maximum wave heights possible once in a given number of years using the simple procedure described in Section 2.

Note that the choice of the type of distribution is not very important. As noted in Van Vledder et al. (1993), in which the authors analyzed three methods for finding extreme values and eight distribution functions, the results do not differ from each other by more than 10% (when determining the wave height possible once in a hundred years).

Fig. 8 shows spatial maps of the height distribution of the maximum (significant) waves, possible once in 1 year, as well as in 5, 10, 25, 50, and 100 years for the components of surface waves and mixed waves.

It follows from Fig. 8 that 10-m waves are not very rare in the Black Sea; in the south-western part they can appear once in 10 years. Once every 100 years, waves of about 12 m (and possibly higher) are possible. The most dangerous areas are the southwestern part of the sea and the region in the central part, adjacent to the southern coast of Crimea. The largest swell is observed in the south-southeastern part of the sea and at the eastern coast. The recurrence of swell waves with a height of 8 m is every hundred years.

4. Conclusions

As a result of this work, a data set of calculated wave fields was processed. The data set consisted of the fields of significant wave heights of the components of surface waves, and mixed (total) waves in the period from 1979 to 2017. The spatial distributions of the maximum waves in the Black Sea provide evidence that favorable conditions for the development of storm waves with significant wave heights of about 12 m may develop in the Black Sea. This means that the real maximum waves can be as high as 18—19 m.

Three regions are clearly distinguished from the wave potential. The time of manifestation of extreme situations is slightly different: in the southwestern part of the sea, extreme events usually occur in January and December; extreme events south of the southern coast of the Crimea Peninsula occur in February; while in the northeastern part of the sea they appear in November.

The southeastern and extreme eastern parts of the sea are most subjected to strong swell.

The interannual variability of maximum wind waves and swell in the sea will be the subject of further research.

Acknowledgments

This work was supported by the Russian Foundation for Basic Research, project no. 18-05-80035. The computer calculations were supported by the Russian Foundation for Basic Research (Projects no. 19-05-00041 and no. 19-45-230002). Analysis of the results was carried out within the State task programs 0149-2019-0014 and 0827-2018-0004. Processing of altimetry data was supported by the Russian Foundation for Basic Research, project no. 18-45-920059.

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