Maximum waves in the Black Sea

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Abstract

In this paper, a comparison of the wind waves parameters calculations in the Black and Azov seas, using two common spectral wave models: DHI MIKE 21 SW and SWAN was made. The fields of the wind waves main parameters (wave heights, periods, directions of propagation) were obtained for a climatic period of time from 1979 to 2018. Comparison of the calculation results shows that with the accepted model settings, the SWAN model, compared with MIKE, overestimates the values of wave heights with weak and moderate waves and underestimates with the extreme ones. Estimation of the maximum wave heights on the Black Sea, possible once in a given number of years, performed on two different models, was made. It showed that for the conditions of the Black Sea the difference between the calculated values of significant wave heights of rare frequency for the MIKE and SWAN models does not exceed 12%. The maximum significant wave heights, possible once in a hundred years, in the Black Sea can reach 11-12 m.

Introduction

Mathematical modeling is a modern and very productive tool for studying of surface waves parameters. At present, spectral models of wind waves have received significant development. Within the framework of regional application, implementations of spectral models, such as SWAN of the Delft University of Technology (Booij, 1999) and MIKE21 SW of the Danish Hydraulic Institute (DHI, 2007), are best known. Unlike the commercial product MIKE 21 SW, SWAN is freely available and, in general, has parameters that are more customizable. There are no fundamental conceptual differences between these programs; therefore, the choice of a particular model as a working tool is determined, in essence, by the personal preferences and abilities of the researcher. In addition, the user-friendly interface and the powerful post-processing provided by MIKE can be opposed by the open SWAN code, which allows combining the wave model with other computational blocks (for example, atmospheric). In general, a combination of factors makes SWAN more common in the scientific community.

Table 1 shows the works published in recent years and devoted to various issues of the spatial and temporal variability of the parameters of the wind waves of the Black Sea.

Table 1: Some publications on Black Sea wave issues in recent years

Model used	Source	Issues
MIKE	Divinsky, Kosyan, 2017	Spatiotemporal variability of the wave climate
	Aydoğan, Ayat, 2018	Long-term trends of significant wave height
	Divinsky, Kosyan, 2018	Climatic peculiarities of the distribution of wind sea and swell
SWAN	Akpinar, Ponce de León, 2016	Assessment of wind re-analyses for modelling storms
	Akpinar A. et al., 2017	Wave energy potential
	Fomin, 2017	The influence of atmospheric cyclones on surface wind waves
	Bingölbali et al., 2019	South-west Black Sea wave climatology based on a downscaling approach
	Rusu, 2019	Wave and wind power resources in the western part of the Black Sea

As follows from the table. 1, with reference to the Black Sea area, both models are successfully used. In this paper, several problems are solved: (1) a comparison of the results of the main wave parameters calculations, performed using the MIKE and SWAN models; (2) an estimation of the maximum waves heights on the Black Sea, possible once in a given number of years, made on the basis of the calculated climatic characteristics of wind waves for the period from 1979 to 2018.

Models description

The MIKE 21 SW and SWAN models are based on the numerical solution of the balance equation for wave energy in spectral form. The main physical processes (wind pumping, whitecapping, energy dissipation due to bottom friction and collapse) are defined by semiempirical functions. In both models, the wave energy dissipation processes due to whitecapping are described by the term (Booij et al., 1999):

$$S_{dw}(\sigma,\theta) = -C_{ds}\left(\frac{\alpha}{\alpha_{PM}}\right)^m \left\{(1-\delta)\frac{k}{\tilde{k}} + \delta\left(\frac{k}{\tilde{k}}\right)^2\right\}\tilde{\sigma}\, E(\sigma,\theta),$$

where $E(\sigma,\theta)$ is the frequency-angular spectrum; σ - frequency; θ - angular coordinate; k - wave number; $\tilde{\sigma}$, $\tilde{k}$ - mean values σ and k; α – the steepness of the waves; α_{PM} - value α for Pierson-Moskowitz spectrum ($\alpha^2_{PM} = 3.02\times10^{-3}$); C_{ds}, m and δ - tuning parameters. We briefly describe the existing features in the model settings.

MIKE 21 SW

The setting up of the model is optimized for the task for wind waves and swell components separating. Let's note the main characteristics of the model:

- 50 spectral frequencies are distributed in the range of periods from 1.6 to 17.3 s, using the 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, i.e. the resolution of the model in directions is 11.25°;
- values of the tuning coefficients, determining the energy dissipation due to whitecapping: $C^*_{ds} = C_{ds}/\alpha^4_{PM}$ = 5.5; δ = 0.15; m = 4.
- separation of wave components is performed using a criterion that takes into account the "age" of the waves.

These settings allow correctly reproduce extreme wave phenomena in a rapidly changing synoptic environment. The results of model verification are detailed in the papers (Divinsky, Kosyan, 2017; Divinsky, Kosyan, 2018).

SWAN

In the used model, the default settings are selected. The main characteristics of the model are as follows:

- 40 spectral frequencies are used in the frequency range of 0.055 - 0.625 Hz;
- discreteness in direction is 10 °;
- values of the tuning coefficients, determining the dissipation of wave energy due to whitecapping: $C_{ds} = 2.36\times10^{-5}$; m = 2; δ =1;;
- an implicit time integration scheme is used in 30-minute increments.

Common settings for models

Both models are implemented on the same unstructured computational grid, covering the entire water area of the Black and Azov Seas and consisting of 20 thousand design elements (Fig. 1).

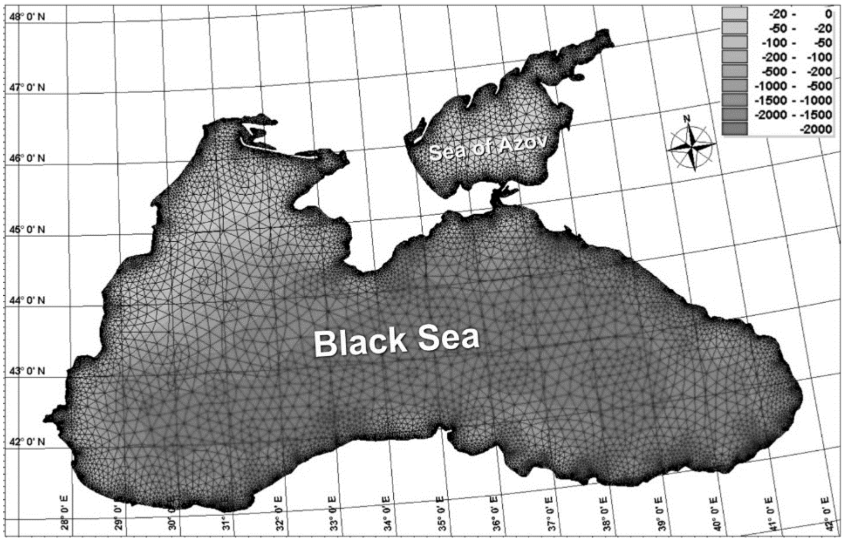


Fig. 1: Bathymetric map (m) and computational grid for the Black and Azov Seas area.

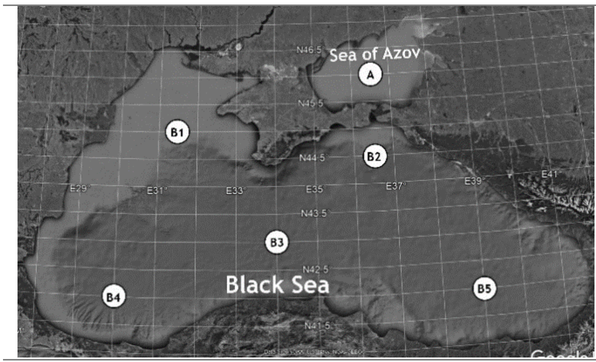
The data of the global atmospheric reanalysis of ERA-Interim, presented by the European Center for Medium-Range Forecasts (http://apps.ecmwf.int), are used as initial wind fields. The considered area is limited by coordinates: in latitude - 40^0N and 47^0N, in longitude - 27^0E and 42^0E. The spatial resolution of the wind fields is the same in latitude and longitude and is 0.25^0, the time step is 3 hours.

Results and Discussion

As a result of calculations over the Black and Azov Seas area, hourly fields of wind wave parameters (wave heights, periods, propagation directions) for the period from 1979 to 2018 were obtained. Calculations are performed separately for two models. We have to note that the results obtained for the freezing Sea of Azov are not quite correct and are rather illustrative.

Let us compare the calculation results obtained using the MIKE and SWAN models for five points in the Black Sea and one in the Sea of Azov. The position of the points indicated in the table. 2

Table 2: Position of points in the Black and Azov Seas area.



Point	Latitude, N	Longitude, E
A	46.0	36.5
B1	45.0	31.5
B2	44.5	36.5
B3	43.0	34.0
B4	42.0	30.0
B5	42.0	39.0

As the test year, 2007 was chosen. In this year the surface waves were characterized by extreme values. Figure 2 shows the series of significant wave heights h_s (2a), periods of the spectral peaks t_p (2b), and average propagation directions (2c).

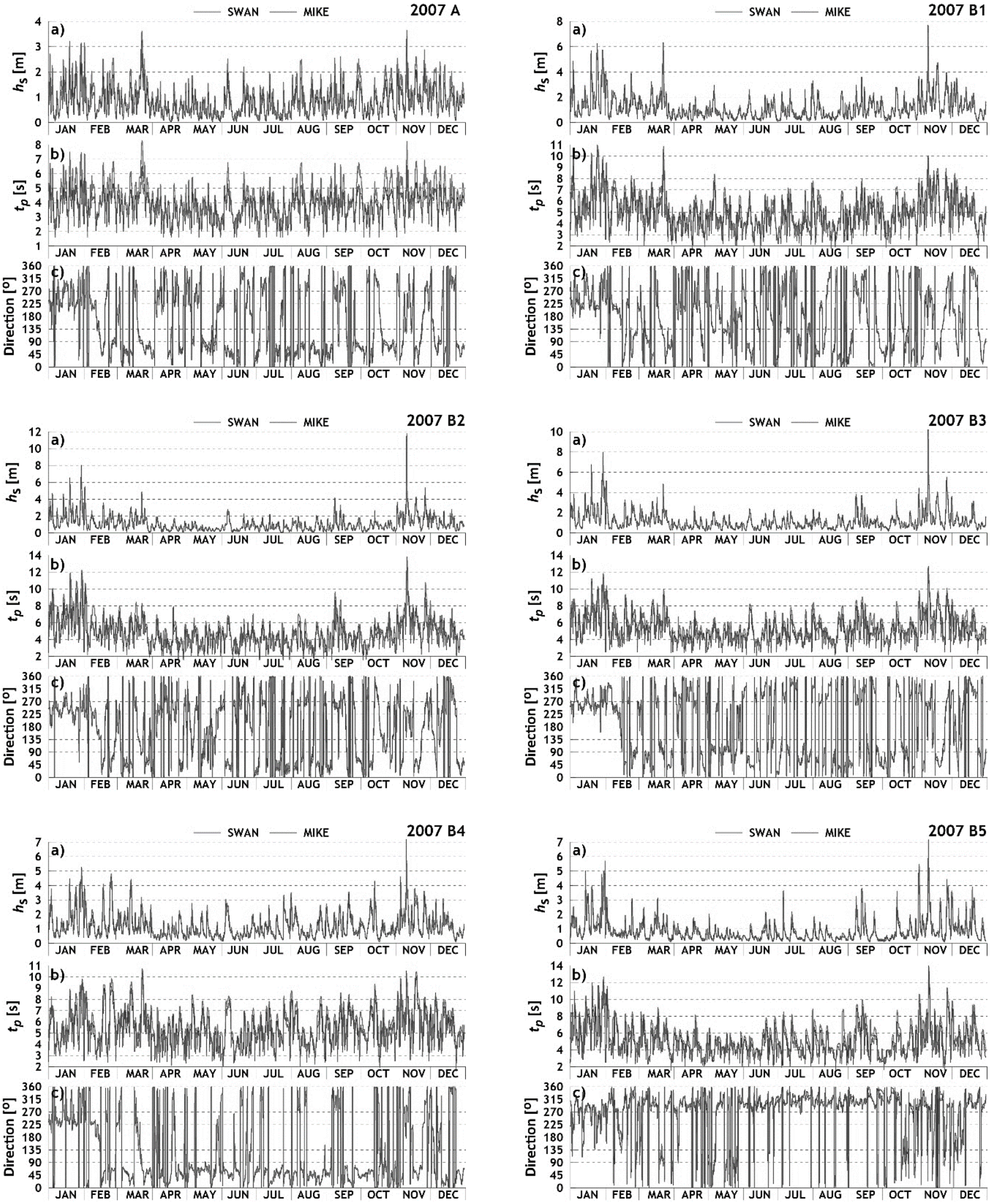


Fig. 2: The series of significant waves heights (a), the periods of the peaks of the spectrum (b) and the directions of propagation of the waves (c), obtained by calculation at given points.

As follows from Fig. 2, both models demonstrate excellent similarity for the Black Sea; but for the Sea of Azov, the difference in the results is much more pronounced. Quantitative criteria for the conformity of the two models for significant wave heights and periods are summarized in Table. 3. The statistical parameters used in the comparison are as follows: bias, root-mean-square error (*RMS*), bias index (*BI*), scatter index (*SI*), and Pearson's correlation coefficient (*r*). If X_M is a value derived from the MIKE model, X_S is based on the SWAN model, then these parameters can be represented as:

$$Mean:\ X_M = \frac{1}{n}\sum_{i=1}^{n} X_M\ ,\ X_S = \frac{1}{n}\sum_{i=1}^{n} X_S\ ;$$

$$Bias = X_M - X_S\ ;$$

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(X_M - X_S\right)^2}\ ;$$

$$BI = \frac{Bias}{X_M X_S}\ ;$$

$$SI = \frac{RMS}{\sqrt{X_M X_S}}\ ;$$

$$r = \frac{\sum_{i=1}^{n}\left(X_M - X_M\right)\left(X_S - X_S\right)}{\sqrt{\sum_{i=1}^{n}\left(X_M - X_M\right)^2\sum_{i=1}^{n}\left(X_S - X_S\right)^2}}\ .$$

Table 3: Statistical analysis of the models MIKE and SWAN conformity

Point	**Significant wave height h_s**				
	Bias	***RMS***	***BI***	***SI***	***r***
A	-0.17	0.28	-0.18	0.30	0.98
B1	-0.07	0.18	-0.06	0.15	0.99
B2	-0.06	0.18	-0.05	0.16	0.99
B3	-0.06	0.15	-0.05	0.13	0.99
B4	-0.13	0.22	-0.11	0.17	0.99
B5	-0.09	0.24	-0.09	0.26	0.97
	Peak wave period t_p				
A	-0.46	0.67	-0.11	0.16	0.96
B1	-0.50	0.73	-0.10	0.14	0.95
B2	-0.55	0.93	-0.11	0.18	0.92
B3	-0.73	0.96	-0.13	0.17	0.93
B4	-0.62	0.84	-0.11	0.14	0.94
B5	-0.68	1.17	-0.12	0.21	0.88

The data of the Table 3 show that for all selected points, the SWAN model gives overestimated, as compared with MIKE, values of both significant wave heights and peak periods of the spectrum. The best coincidence between model calculations is observed in the central part of the Black Sea (point B3), the worst - in the southwestern part (B5). In the shallow water (maximum depths of about 12 m) of the Sea of Azov, the differences between the models are unacceptably large and require separate consideration, beyond the scope of this work.

The obtained results characterize the average situation. If to display a regression of the calculated wave heights (Fig. 3) on one graph, a curious detail is found. SWAN confidently demonstrates overestimated heights for low and moderate waves. In strong and extreme storms with significant wave heights, exceeding 4.5–5 m, the MIKE model gives higher values (compared to SWAN).

Unfortunately, the very weak coverage of the Black Sea area by direct instrumental observations (with a wide geographic coverage) does not make it possible to fully appreciate such differences between the models.

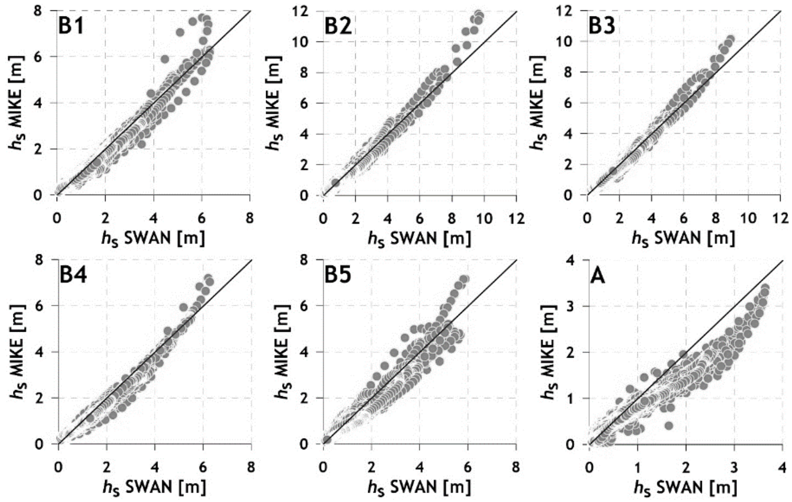


Fig. 3: The ratio of significant wave heights obtained by the two models at selected points (data for 2007).

For the Black Sea, the most representative are the wave experiment data, performed in 1996-2003 on the basis of the SB of the IO RAS. In the framework of the international program NATO TU-WAVES, in order to study the wave climate of the Black Sea in the coastal zone of the city of Gelendzhik, the Directional Waverider Buoy was installed (Kos'yan et al., 1998). The Dutch company Datawell manufactured this buoy. The coordinates of the installation point were 44º30'40 N, 37º58'70 E, the depth of the site was 85 m, which for all observed waves corresponds to the conditions of deep water. The largest of the recorded wave heights for the entire observation period was observed in February 2003 and amounted to 12.43 m. Using the example of this storm, we compare the results of calculations obtained using the MIKE and SWAN models.

Let's pay attention to some features of the experiment. The software and hardware part of the Datawell wave buoy (at least the devices we had at our disposal in 1996-2003) provided three blocks of information about wind wave parameters for each measurement period:

- firstly, 256 consecutive waves are counted and wave statistics are determined from them;

• further, on the basis of a half-hour series of observations, two-dimensional spectra are calculated, which ultimately give the integral parameters of waves;
• finally, the 20-minute series of “raw” observations of free-surface elevations accumulate and remain, allowing later to independently determine the wave characteristics.

The formation of all three blocks takes near one hour and is tied to a specific observation period. These information blocks are separated in time, so the wave parameters, defined for these blocks, may (and even should) be different. Let’s note, also, that the analysis of waveforms and spectra gives two different estimates of "significant wave heights". For waveforms, $h_{1/3}$, is calculated, i.e. average wave height from one third of the largest waves of the ranked series; The processing of the spectra directly gives a significant wave height, determined through the zero moment of the spectrum. Naturally, these two assessments are somewhat different, but we will assume that for our purposes these differences are not significant.

Fig. 4 presents data from observations of wind wave parameters during an extreme storm in early February 2003. The Y scale gives a reading in hours of January 27.

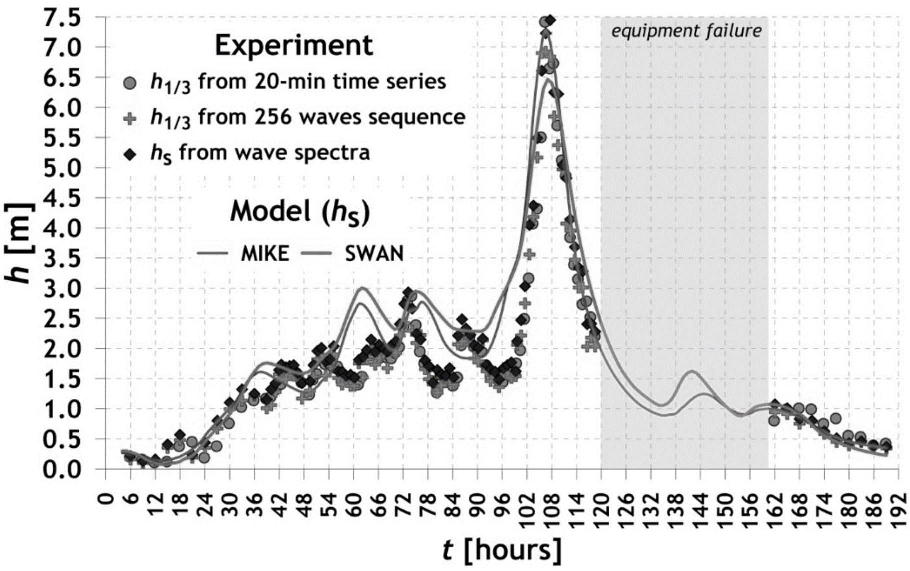


Fig. 4: Comparison of experimental and model wave heights in an extreme storm.

For the same observation rime, during the period of maximum development of the storm, analysis of 256 successive waves gives the maximum height in the storm (in terms of $h_{1/3}$) of 6.92 m, processing the 20-minute data generated at the end of the observation hour gives the value of $h_{1/3}$ = 7.42 m. In the middle of an hour of observations, a significant wave height was 7.45 m. The results of calculations by the models: MIKE - h_s = 7.30 m, SWAN - h_s = 6.46 m. From fig. 4 it is clearly seen that the wave heights obtained using the SWAN model, on average, slightly exceed the calculated values using the MIKE model. When the waves go to the extreme phase and when the wave heights exceed the 4.5 m threshold, the MIKE results exceed the SWAN and, in general, are more consistent with the experimental data.

Thus, we can confidently assert that with the model settings made, the SWAN model, in comparison with MIKE, overestimates the values of the wave heights with weak and moderate waves and underestimates with the extreme ones.

Let us find out how these differences affect the estimates of the heights of waves of rare frequency. To estimate the heights of surface waves, we apply the method of annual maxima based on the integral Gumbel distribution function (Lopatoukhin et al., 2000; Kamphuis, 2000):

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

where *F(h)* is the probability that the wave height does not exceed the value of *h;* α, β are the parameters, determined for each specific point by a given series of annual maximums of wave heights. The parameters α and β are determined for each node of the computational grid by the least squares method. From (1) follows the expression for the wave height corresponding to a given value of quartile *F*.

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

Taking into account (2), the estimation of the wave height, possible once in *T* years, is defined as a quartile (1–1/*T*) 100% of the distribution probabilities (1):

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

The result of the above procedure is the field of significant wave heights, possible once in a given number of years. Wave heights, possible once a year, as well as once every 5, 10, 25, 50 and 100 years were analyzed. Fig. 5 shows the calculated fields of wave heights (in terms of significant) in the areas of the Black and Azov Seas, possible once a year.

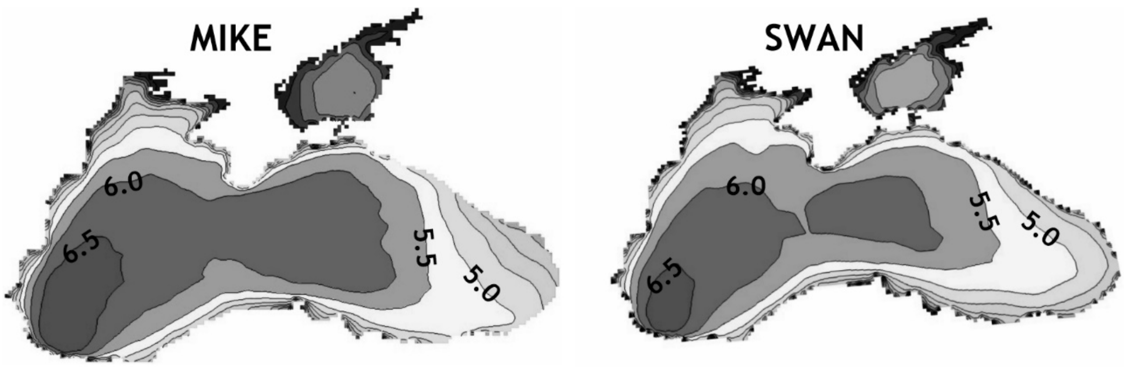


Fig. 5: Calculated fields of significant wave heights (m) in the areas of the Black and Azov Seas, possible once a year.

As follows from fig. 5, the results of calculations for the MIKE and SWAN models, in general, correspond to each other. The region of maximum values is confined to the southwestern part of the Black Sea, occupying a slightly larger space in MIKE than in SWAN. Let us compare the results of model calculations at six selected points (Table 2) in the waters of the Black and Azov Seas. In fig. 6 for these points the values of significant wave heights, possible once in a given number of years, are presented and in fig. 7 - the difference (in percent) between the values of significant wave heights, possible once in a given number of years, obtained by the models MIKE and SWAN.

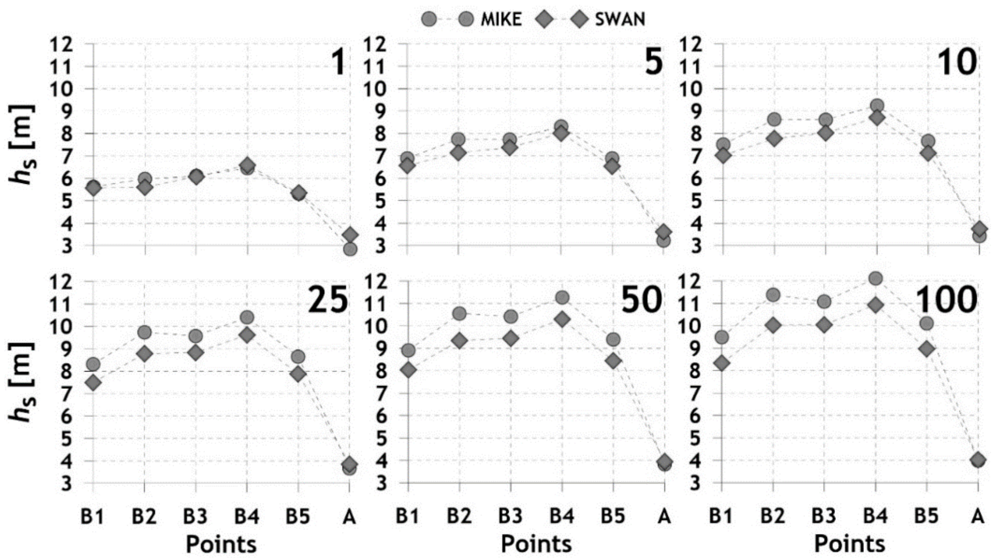


Fig. 6: Significant wave heights, possible once in a given number of years, at selected points of the area.

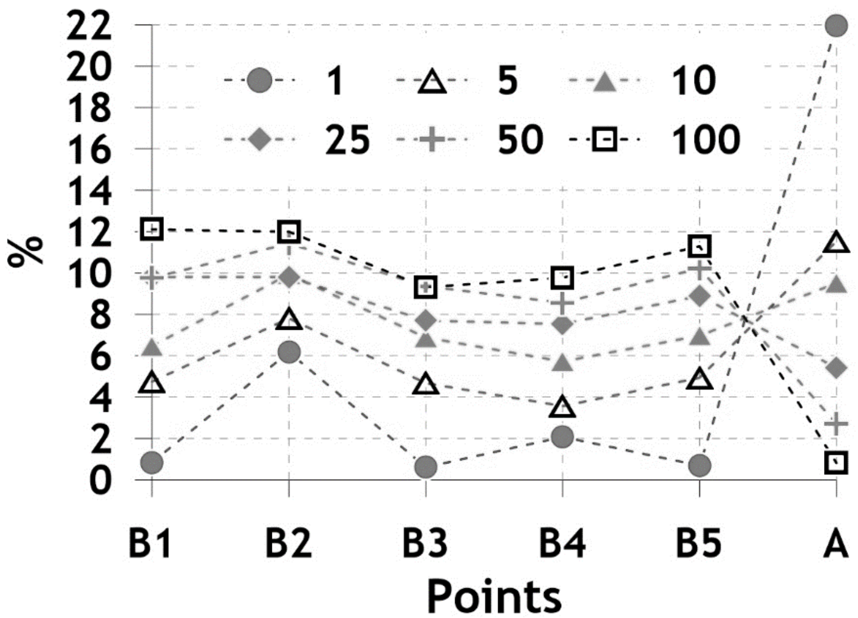


Fig. 7: The difference (in percent) between the values of significant wave heights, possible once in a given number of years, obtained by the models MIKE and SWAN.

As follows from figs. 6 and 7, for the conditions of the Black Sea, the difference between the calculated values of the significant heights of the waves of rare repeatability does not exceed 12%. In absolute terms, this difference is of the order of 1 m for wave heights possible once every 100 years: calculation using the MIKE model gives the magnitude of significant wave heights of 12.1 m, and for SWAN it is 10.9 m. For wave heights possible once a year, in the Black sea both models give almost identical results, except for the northeastern region (point B2). In general, on the Black Sea, with an increase in the repeatability period, the difference between the model calculated values increases. This is expected, since the MIKE model is likely to reproduce extreme wave phenomena better. For the Sea of Azov, the situation is reversed, which is associated with physical limitations in shallow water conditions.

Conclusion

As a result of the calculations carried out in the Black and Azov Seas areas, fields of hourly data were obtained for the main parameters of wind waves (height period, periods, distribution) for the period from 1979 to 2018. The calculations were performed separately for two models: MIKE 21 SW and SWAN.

The calculation results comparison shows that the SWAN model gives, in general, overestimated, as compared with MIKE, values of both significant wave heights and peak periods of the spectrum. The best coincidence between model calculations is observed in the central part of the Black Sea, the worst - in the southwestern part. In the freezing, shallow water and the limited acceleration path of the Sea of Azov, the differences between the models are unacceptably large and require separate detailed consideration.

We have to note that the SWAN model shows overestimated heights for low and moderate waves. In strong and extreme storms with significant wave heights exceeding 4.5–5 m, the MIKE model gives higher values (compared to SWAN).

Thus, with the adopted model settings, the SWAN model, compared to MIKE, overestimates the values of the wave heights with weak and moderate waves and underestimates with the extreme ones.

The estimation of the maximum wave heights on the Black Sea, possible once in a given number of years, performed on two different models, showed that for the conditions of the Black Sea the difference between the calculated values of significant wave heights of rare frequency for the MIKE and SWAN models does not exceed 12%. The maximum significant wave heights, possible once in a hundred years, in the Black Sea can reach 11-12 m.

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Keywords

Wave climate; Black Sea; Numerical modeling; DHI MIKE 21 SW; SWAN