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MARINE PHYSICS

Testing and Verifying the Wind Wave Model with an Optimized Source Function

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Abstract—With the purpose of revealing the actual advantages of the new source function that was earlier proposed in [5] for use in numerical wind wave models, its testing and verification was carried out by means of modification of the WAM (Cycle-4) model. The verification was performed on the basis of a comparison of the results of wave simulation for a given wind field with the buoy observation data obtained in three oceanic regions. In the Barents Sea, this kind of comparison was made for wave observations from a single buoy with an interval of 6 hours for a period of 3 years. In two regions of the North Atlantic, the comparison was performed for 3 buoys in both regions for observation periods of 30 days with an interval of 1 hour. Estimations of the simulation accuracy were obtained for a series of wind wave parameters, and they were compared with the original and modified WAM model. Advantages of the modified model consisting of the enhancement of the calculation speed by 20–25% and a 1.5- to 2-fold increase in the simulation accuracy for the significant wave height and the mean period were proved.

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1. INTRODUCTION

The human activity related to the sea requires regular calculations of the wind wave parameters for the resolution of numerous applied problems. Among them, two may be regarded as the most important. The first problem is defined by the necessity of calculations and forecasts for navigation needs, while the other is related to the engineering calculations of loads on the coasts and coastal constructions affected by wave impact. Herewith, along with the time required for the calculations, the issue of their accuracy is the most important, since the discrepancies between the results obtained with different models appear to be too great [2, 3, 9, 11].

All the present-day numerical models for wind waves are based on the solution of the evolution equation for a two-dimensional wave spectrum $S(\sigma, \theta, \mathbf{x}, t)$ specified in the space of wave frequencies σ and angles of wave propagation θ and defined over the geographical coordinates $\mathbf{x}$ and the time t. In a generalized presentation, this equation has the form

$$\frac{dS(\sigma,\theta,\mathbf{x},t)}{dt} = F(N,\mathbf{W},\mathbf{U}) = In + Nl - Dis. \quad (1)$$

In its left-hand part, this equation contains the spectrum derivative with respect to time, and the right-hand side is a source function, which depends both on the wave spectrum and on the external factors of wave formation such as the local wind $\mathbf{W}(\mathbf{x}, t)$ and the local currents $\mathbf{U}(\mathbf{x}, t)$.

The source function F involves the physical concepts used in the model that determine the mechanisms of the wave spectrum evolution [3, 7]. Here, three terms are generally used: the mechanism of the energy exchange between the waves and the atmosphere *In*, the mechanism of conservative nonlinear interactions between the wave components *Nl*, and the mechanism of the energy losses *Dis* related to their breaking and interaction with the turbulence in the upper water layer. Precisely the differences in the presentation of the above components of the source function define the differences between the models. In particular, with respect to the degree of justification of the parameterizing of the *Nl* term, different generations of the models are distinguished [11]. The differences in the presentation of the left-hand part of evolution equation (1) and in the implementation of its numerical solution mostly refer to the mathematics of the models and also determine their particular features. These differences define the fields of application of the models (account for the

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earth's sphericity, the wave refraction over inhomogeneities of the bottom and currents, etc.).

At present, the most wide-spread are three models referring to the third generation: WAM [12], WAVEWATCH (WW) [10], and SWAN [6]. The former two models are mostly used for the solution of the problems of global wave forecasting over deep water, while the latter one is a version of the spreading of the first model in a shallow-water case and is used for regional purposes. These models are rather well tested and provide satisfactory results. The domestic models available [1, 13] also meet the requirements of the solution of most of the practical problems, though differ from the above-listed models. Model [1] refers to the class of the second generation of spectral–parametric models, while model [13], in terms of its basic concept, fundamentally differs from all the Western discrete models (being an essentially Russian development) and is based on the theory of the narrow-directed approximation of wave spectra elaborated by Acad. V.E. Zakharov. It refers to the class of the third generation of discrete models.

Recently, the appearance of new scientific results and the continuous expansion of applied problems caused the necessity of the development of a modern model of a new generation. This, first, refers to the modification of the source function *F*. One of the versions of this kind of solution was suggested in [5].

In [5], based on a comparative analysis of the terms of the source function in present-day models and the results of the studies performed during the past five years, the author suggested a version of its presentation optimal in terms of the accuracy–computation time criterion. He also presented a theoretical justification of the advantages of the new source function and showed, using a series of test experiments, the high degree of its adequacy to the empirical evidence available. Therefore, he speculated that the *F* parameterization suggested may serve as a basis for the creation of a model of a new (fourth) generation.[1]

In this paper, using the example of a comparison between the calculations and buoy wave measurements, we will try and show that even a simple introduction of the optimized function from [5] into the "body" of the WAM model (Cycle 4) results in an essential improvement of the quality of the wave calculations. This kind of verification has a fundamental significance since it confirms the fact of the creation of a scientific basis for the construction of a Russian national model of a new generation.

[1] In addition, it should be added that a significant improvement of the operation speed and calculated accuracy may also be achieved using the new semi-Lagrangian numerical scheme for the solution of Eq. (1) that was proposed and tested by Lavrenov [4]. This aspect of the model enhancement requires a special discussion.

2. BRIEF DESCRIPTION OF THE MODEL AND THE CALCULATION TECHNIQUE

2.1. Optimized Source Function

The term that represents the energy exchange between wind and waves *In* is specified in the commonly used form [7]:

$$In = \beta(\sigma, \theta, u^*)\sigma S(\sigma, \theta). \tag{2}$$

In our version, the increment of the wave growth $\beta(\sigma, \theta, u^*)$ has the form

$$\beta = \max\left\{-b_L, \left[0.04\left(\frac{u_*\sigma}{g}\right)^2 + 0.00544\frac{u_*\sigma}{g} + 0.000055\right]\cos(\theta - \theta_w) - 0.00031\right\}, \tag{3}$$

where σ and θ are the frequency and the angle of propagation of the wave component, u_* is the friction velocity, g is the gravity acceleration, and θ_w is the direction of the local wind. Note that the parameterization of β includes the condition of the existence of a negative β value whose limit value equals

$$b_L = 0.000005. \tag{4}$$

The negative β value means that, in the case when waves overrun the local wind, they give back their energy to the wind.

Generally speaking, in the optimized source function, the conversion from the wind W_{10} at the standard level z = 10 m to the friction velocity u_* is performed with the use of a special unit of the dynamical near-water layer (DNWL), whose complete description is presented in [5]. However, in the calculations presented here, we didn't use the DNWL unit; instead, we used the u_* value calculated within the "body" of the WAM model (Cycle 4).[2]

The *Dis* term has an original theoretically justified parameterization according to the formula

$$Dis(\sigma,\theta,S,W) = \tilde{\gamma}(\sigma,\theta,W)\frac{\sigma^6}{g^2}S^2(\sigma,\theta), \tag{5}$$

in which the dimensionless function $\tilde{\gamma}$ = (σ, θ, W) is specified as

$$\tilde{\gamma}(\sigma,\theta,W) = c(\sigma,\theta,\sigma_p)\max[0.00005, \beta(\sigma,\theta,u_*)]. \tag{6}$$

Here, the value $\beta(\sigma, \theta, u_*)$ is defined by formula (3), while, in these calculations, the dimensionless function $c(\sigma, \theta, \sigma_p)$, which describes details of the process of dissipation in the frequency region of the maximum of the σ_p spectrum, is specified as

[2] Verification of the DNWL unit requires individual measurements of both the wave spectrum S (σ, θ) and the friction velocity u_*; therefore, it remains a subject of further studies.

$$c(\sigma, \theta, \sigma_p) = 45\max[0, (\sigma - 0.5\sigma_p)/\sigma]T(\sigma, \theta, \sigma_p), \quad (7)$$

at an angular dependence of the form

$$T(\sigma,\theta,\sigma_p) = \left\{1 + 4\frac{\sigma}{\sigma_p}\sin^2\left(\frac{\theta - \theta_w}{2}\right)\right\}\max\left[1, 1 - \cos(\theta - \theta_w)\right]. \quad (8)$$

Note that the parameterization of *Dis* suggested in (6) implies the condition of the existence of a nonzero level of energy losses by waves at frequencies on the order of the peak spectral frequency σ_p or lower, which reflects the fact of the existence of background dissipation processes. This element was introduced into the *Dis*tribution parameterization precisely in model [5].

In order to represent the *Nl* term in the source function considered, we use an accelerated (fast) version of the discrete interaction method DIA (FDIA), which showed its high efficiency [8]. Briefly speaking, the acceleration effect is reached owing to the rejection of the cumbersome procedure of interpolation of the current spectra over the calculation grid of the wave components σ and θ, which is contained in the original DIA version that is used in WAM and WW [10, 12]. The numerical implementation of the DIA method is as follows [5].

The calculation grid of the frequencies–angles (σ, θ) is specified using the presentation that is commonly accepted in modern models

$$\sigma(i) = \sigma_0 e^{i-1} \quad (0 \le i \le I), \quad (9)$$

$$\theta(j) = -\pi + j\Delta\theta \quad (0 \le i \le J). \quad (10)$$

Here, σ_0 is the lower boundary of the frequency band, e is the exponential increment of the frequency grid, I is the number of frequencies considered, $\Delta\theta = 2\pi/J$ is the angular resolution in radians, and J is the number of directions assessed. Further, we use the values of these parameters typical of the WAM model version (Cycle 4):

$$\sigma_0 = 2\pi 0.05 \text{ p/c}, e = 1.1, I = 30, J = 24, \Delta\theta = \pi/12. \quad (11)$$

In this case, the optimal configuration of four interacting waves in the FDIA version is specified by the following relations:

(a) with respect to the frequencies

$$\sigma_1 = \sigma e^3, \quad \sigma_2 = \sigma e^3, \quad \sigma_3 = \sigma e^5, \quad (12a)$$

(b) with respect to the angles

$$\theta_1 = \theta + 2\Delta\theta, \quad \theta_2 = \theta + 2\Delta\theta, \quad \theta_3 = \theta + 3\Delta\theta \quad (12b)$$

at the known values of σ and θ for which the calculation loop is arranged. In this loop, the expression for the term $Nl[S(\sigma, \theta)]$ is calculated from the known formulas [7]

$$NL(\sigma, \theta) = I(\sigma_1, \theta_1, \sigma_2, \theta_2, \sigma_3, \theta_3, \sigma, \theta), \quad (13a)$$

$$NL(\sigma_3, \theta_3) = I(\sigma_1, \theta_1, \sigma_2, \theta_2, \sigma_3, \theta_3, \sigma, \theta), \quad (13b)$$

$$NL(\sigma_1, \theta_1) = -I(\sigma_1, \theta_1, \sigma_2, \theta_2, \sigma_3, \theta_3, \sigma, \theta), \quad (13c)$$

$$NL(\sigma_2, \theta_2) = -I(\sigma_1, \theta_1, \sigma_2, \theta_2, \sigma_3, \theta_3, \sigma, \theta), \quad (13d)$$

where

$$I(\sigma_1,\theta_1,\sigma_2,\theta_2,\sigma_3,\theta_3,\sigma,\theta) = C\sigma^{11}[S_1S_2(S_3 + (\sigma_3/\sigma)^4 S) - S_3S((\sigma_2/\sigma)^4 S_1 + (\sigma_1/\sigma)^4 S_2)]. \quad (14)$$

In formulas (13, 14), we used a contracted notation $S_i = S(\sigma_i, \theta_i)$, while the index "4" is omitted. The values of σ_i and θ_i for the indices $i = 1, 2, 3$ are given by relations (12). In the optimized FDIA version, the adjusting constant C in the above source function equals 12 000.

2.2. CALCULATION TECHNIQUE

The calculations were performed by introducing the above-described source function into the codes of the WAM numerical model; actually, this meant its modifying. The version obtained was conventionally referred to as NEW. In this way, the advantages of the new source function were determined from a comparison between the results obtained with the original and modified versions of the WAM model. Herewith, owing to the identity of the codes of the WAM model (Cycle 4), all the differences in the results were caused exclusively by the properties of the new source function, i.e., by the implied new physics of the wave evolution.

Previous to verifying the NEW model, we performed a series of test calculations. Among them, the most important was the direct fetch test (see [3, 5, 11] for the description of the test). The results of this test allow one to estimate the quality of the model tuning with respect to the empirical relations for the wave evolution under a constant wind W_{10}. In order to do this (within the frameworks of the WAM model calculating technology), we used a symmetrical near-equatorial test aquatic area 30 × 30 points in size with different spatial intervals ΔX and ΔY. The results of the calculations for the case of the $\Delta X = \Delta Y = 90$ km and $W_{10} = 20$ parameters in Fig. 1 show that, with respect to the empirical dependences of the wave growth, the NEW model is tuned not worse that the original WAM model. As one can see from Fig. 1, the results of the calculations well fit the range of scattering of the empirical data cited in [7].[3]

The subsequent stage of the studies was the verification of the NEW model. In this relation, note that this requires the fulfillment of a series of conditions. Among them, the principal ones are the following: (a) the availability of a database of wave observations, (b) the availability of reliable wind fields over a sufficiently dense spatiotemporal grid, and (c) the availability of a well elaborated mathematical base of the numerical model of form (1). In addition, a known wind wave

[3] See [5] for a detailed description of the tests of the new source function.

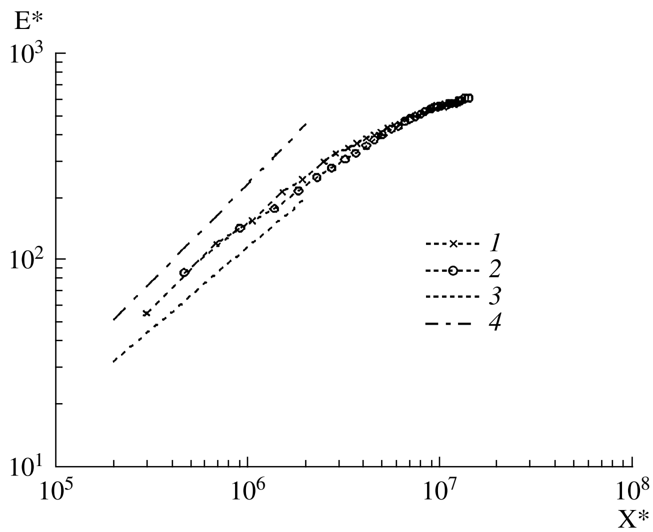

Fig. 1. Results of a direct fetch test for the dependence of the dimensionless energy $E^* = \mathrm{E}g^2/u_*^4$ on the dimensionless fetch $X^* = \mathrm{X}g/u_*^2$. *1*—WAM; *2*—NEW; *3* and *4*—empirical dependences for stable and unstable stratifications after monograph [7].

model should be taken as a reference. In this study, we met the conditions listed in the following way.

We surveyed three kinds of oceanic areas for which data of wave observations were available. For the first kind, we used the data of buoy measurements of wave parameters in the Barents Sea; they lasted over three years with an observation frequency of six hours (a total of 4000 points of observations). Since the buoy data available refer only to the observations of the significant wave heights H_s and to the wave periods close to the period of the wave spectral peak T_m, a comparison with the observations was feasible only for the wave parameters cited. The geometry of the calculation domain is shown in Fig. 2. It covers the area from 30°W to 30°E and from 60° to 80°N. The spatial steps of the calculation grid were 1.5 degrees over the longitude and 0.5 degree over the latitude.

As the wind field, we used the four-times-per-day components of the wind speed at a 10-m height obtained from the data of the reanalysis performed at the NCEP/NCAR Center of the United States. The reliability of the wind data was tested in [2]. In the same paper, for the aquatic area considered, waves were calculated using the WAM Cycle-4 and WW-III models. Since the WAM model showed the lowest error in the calculations of the wave heights, it was chosen as the reference one. Therefore, the new source function was also introduced into the mathematical "body" of the WAM model.

The second and the third calculating regions represented two parts of the North Atlantic (Fig. 3). The boundaries of the calculated domain run along 80°W and 10°E and along 15° and 70°N. For this area, we used the data from British (eastern part of the North Atlantic) and American (western part of the North Atlantic) buoys for January 2006 available at an observation frequency of one hour (2100 observation points in each of the regions assessed). The calculate grid had a resolution of 1.25 degrees over both the latitude and longitude since we intended to use the wind field precisely with this spatial resolution. However, based on the results of a comparison of the wind data from different sources, we decided to use the wind field from the same NCEP/NCAR center with a resolution of 2.5 degrees and an interval of 6 h. This forced choice

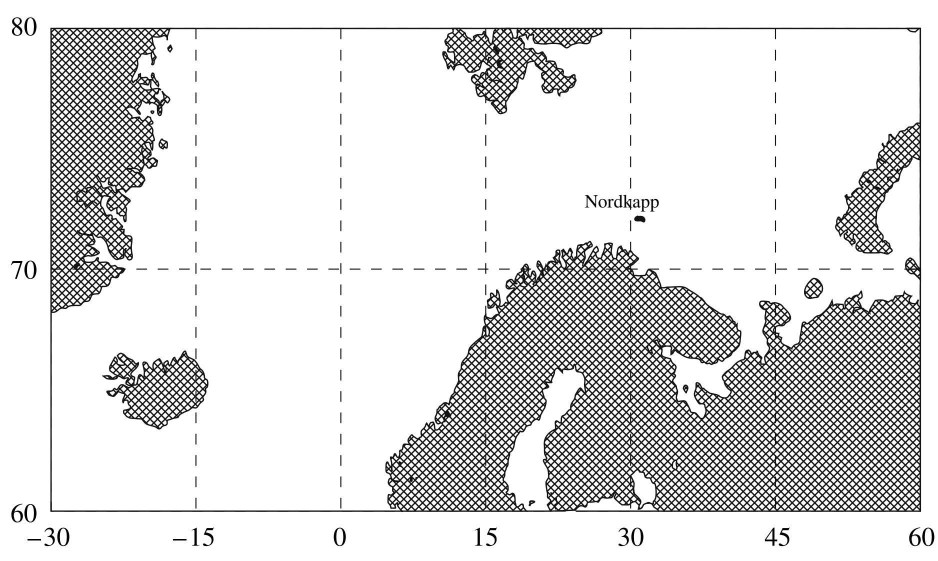

Fig. 2. Calculation domain in the Barents Sea and the position of the "Nordkapp" Norwegian buoy.

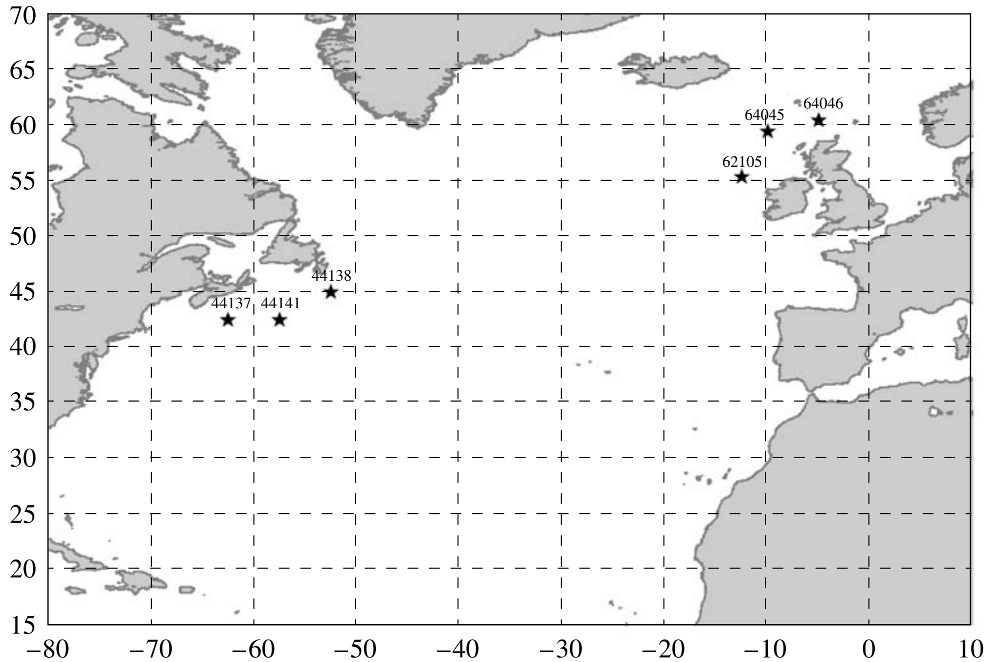

Fig. 3. Calculation domain in the North Atlantic with positions and numbers of buoys.

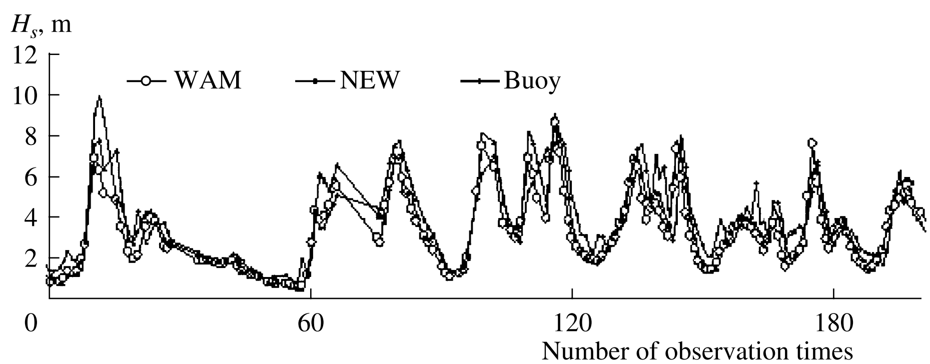

Fig. 4. Temporal evolution of significant wave heights from the models and according to the buoy data in the Barents Sea.

required the wind fields to be interpolated both over space and time; this, naturally, negatively affected the quality of the wave calculations. Nevertheless, in our opinion, the comparative analysis of the calculation errors with different models performed by us appeared to be rather reliable.

3. RESULTS OF THE CALCULATIONS

3.1. Barents Sea

A clear comparison between the results of the calculations of significant wave heights H_s obtained with the two models considered is shown in Fig. 4; they refer to the period from December 1991 to January 1992, when the strongest storms were observed. Visually, this figure suggests a good correspondence of the dynamics obtained with both of the models and the dynamics of the variability of the actual wave heights. Quantitatively, the characteristics of the differences in the model accuracies may be obtained using routine statistical procedures. For example, the most important quantitative parameter that characterizes the calculate accuracy is the root-mean-square deviation of the significant wave heights ΔH_s and mean periods ΔT_m. Precisely these values for the models used are listed in Table 1 for the entire verification period.

As a remark, we should note that, in the qualitative respect, good coincidence between the calculated and observed values is characteristic for both of the models. This confirms the known opinion that the WAM model is the best one in the field of hydrometeorology considered [7, 9]. Meanwhile, along with this, precisely the

Table 1. Root-mean-square errors of the calculations in the Barents Sea region

Model	ΔH_s, m	ΔT_m, s
WAM	0.82	1.4
NEW	0.75	1.1

Table 2. Root-mean-square errors of the calculations in the eastern region of the North Atlantic

	Buoy 64046		Buoy 64045		Buoy 62105	
Model	ΔH_s, m	ΔT_m, s	ΔH_s, m	ΔT_m, s	ΔH_s, m	ΔT_m, s
WAM	1.15	2.8	1.26	3.8	1.14	3.5
NEW	0.75	1.8	0.79	2.1	0.61	1.8

NEW model provides a more accurate presentation of extreme waves (Fig. 1), while the quantitative characteristics of the errors (Table 1) suggest its significant advantages as compared to the WAM model.

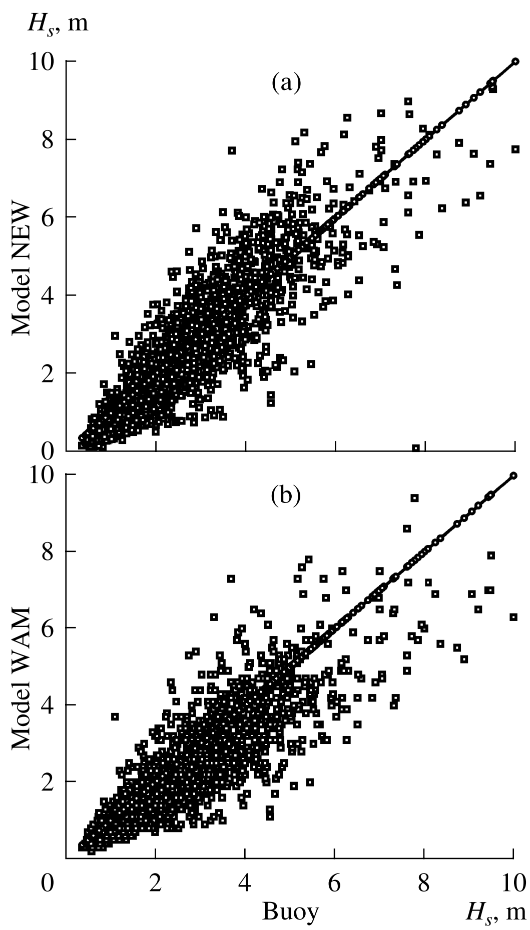

Fig. 5. Correlation between the wave heights H_s measured with the help of the buoy and the heights H_s calculated with the (a) NEW and (b) WAM models.

For the sake of objectivity, we should note the effect of the underestimation of extreme H_s values in the calculations with all of the models; it is caused by their "persistent" character as compared to the actual wave dynamics. This effect is clearly represented by the scattering diagram shown in Fig. 5: all the waves with actual values $H_s > 8$ m are underestimated in both of the models (this effect is stronger in the WAM model). In order to clarify the reasons for the appearance of this defect in the model and to seek methods for its correction, one has to use wind fields with a high temporal resolution, for example, with a time step of 1 h. Since at present these kinds of wind fields for oceanic areas are not available, the solution of this problem remains the purpose of future studies.

3.2. North Atlantic

The results of the calculations for the second and third cases, as well as for the first water area, show good correspondence of the numerical values of the height H_s to its temporal dynamics similar to that shown in Fig. 4. The coincidence of the wave periods is not so good (Tables 2, 3). Both of the models overestimate period values, which is, to a great extent, caused by the technical differences in the determination of the T_m values from the buoys and in the numerical models. Nevertheless, on the whole, one observes a significant improvement in the calculation accuracy of both the H_s and T_m values with the new model as compared to the WAM model.

Taking into account the systematic accuracy improvement with the NEW model in all three regions considered and for all the buoys at a time, we may infer that, in our verification techniques, this accuracy improvement is completely caused by the more accurate physical model provided by the new source function. This is the main result of the studies performed.

3.3. Problem of the Calculation Speed

The results presented give a rather complete general idea of the accuracies of the models. In addition, one should note the significant enhancement in the calculation speed for the model with an optimized source function as compared to the standard WAM model; it reaches about 25–30% of the operation time of the central processor. This effect of acceleration of the calculations is mostly related to the optimization of the calculation of the *Nl* term that was mentioned above and described in detail in [8].[4] In particular, for test calculations of direct fetch, an estimate of the time of operation of the central processor for the performance of selected procedures that take more than 10% of the total operation time performed with the PROFILE option of the

[4] As follows from the above considerations, the corresponding modified version of the WW model should also feature an enhanced calculation speed.

processor of the Apollon workstation is presented in Table 4. As far as, in this respect, the main parameter is the relative time distribution over the procedures, the issue of the processor speed in this case is not decisive.

It is interesting to note that the procedures that were not changed in the course of the modification (for example, the "Implish" procedure of the implementation of the numerical scheme) take similar times in absolute units, while the modified procedures require different times. Herewith, the overall gain in the calculation speed and the reasons for it are seen both in absolute and relative units.

In its turn, the relative proportion is a universal parameter that characterizes the time "weight" of the procedures. As is evident from Table 4, the "Snonlin" procedure takes the bulk of the time in the WAM model even despite the maximal compression of the full kinetic integral that describes the nonlinear evolution mechanism to a single term of the enormous number of summings under the integral sign. This is described in detail in [5, 7, 8]. Therefore, the acceleration of the "Snonlin" procedure is a very efficient "intellectual" advantage of the new source function.

4. CONCLUSIONS

Thus, the results of testing and verifying the new source function used in the mathematical shell of the standard WAM model showed the advantages of the new version. They include the 20–25% acceleration of the calculation process of wave fields at the conservation of all the other model parameters and the 1.5- to 2-fold reduction in the errors of the calculations of the main wave parameters. Herewith, the systematic character of the accuracy improvement in all of the cases assessed is completely provided by the better physical justification of the model source function suggested. This inference allows one to assert that the parameterization of F proposed may form a basis for the creation of a Russian model with characteristics that would overcome the world counterparts (see also Footnote 1).

In the future, in view of the perspectives of the development of the modeling of wind wave evolution, we have to note the following issue. An analysis of the curves such as those shown in Fig. 4 shows that the greatest contribution to the mean error is made by the deviations of the calculations from the observations in the range of extreme values of wave parameters and in the temporal phases of wave attenuation. In our calculations, the relative error in the parameters considered in the range of their extreme values was reduced by 20–25%. It is natural to suggest that these errors are related to the insufficient accuracy of the wind field used. In this respect, it is interesting to present the estimates of the expected errors depending on the expected errors of the wind field specification.

Note that the disadvantages of the model such as the underestimation of the extreme values of the heights H_s

Table 3. Root-mean-square errors of the calculations in the western region of the North Atlantic

	Buoy 44138		Buoy 44141		Buoy 44137	
Model	ΔH_s, m	ΔT_m, s	ΔH_s, m	ΔT_m, s	ΔH_s, m	ΔT_m, s
WAM	1.19	0.8	0.88	0.51	0.51	0.81
NEW	1.0	0.6	0.73	0.42	0.45	0.69

Table 4. Distribution of the operation time of the central processor over the procedures for the two versions of the WAM model

Model type	Procedure name (*its function*)	Time spent, s	Relative time, %
Original WAM	Snonlin (*calculation of the Nl term*)	314.20	47.5
	Implsch (*schematic of numerical solution* (1))	107.25	16.2
	Sinput (*calculation of the In term*)	105.75	16.0
	All procedures together	661	100
Modified WAM (NEW)	Snonlin	143.82	27.1
	Implsch	106.52	20.1
	Sdissip (*calculation of the Dis term*)	83.84	15.8
	Sinput	70.59	13.3
	All procedures together	530	100

and overestimation of the values of the mean period T_m as compared to the data of observations represent natural model errors related to the insufficient reliability of the wind field $\mathbf{W}(\mathbf{x}, t)$ used; they are inevitable at the present stage of the development of atmosphere circulation modeling. Indeed, applying different typical empirical dependencies of the dimensionless wave energy $E^* = \mathrm{E}g^2/u_*^4$ of the dimensionless fetch $X^* = \mathrm{X}g/u_*^2$ (see, for example, [7]) in the form

$$E^*(X^*) = 4.7 \times 10^{-4} X^{*0.95}, \tag{15}$$

one can readily show that, at a fixed fetch, the wave energy is proportional to the squared wind speed

$$E \propto u_*^2 \propto W_{10}^2. \tag{16}$$

Thus, an error on the order of ΔW in specifying the W_{10} value may result in a relative error of the wave energy on the order of $\Delta E/E \cong 2\Delta W/W$ even in a well-tuned model. At values of ΔW of 1–2 m/s and W_{10} of 10 m/s, which are typical of the wind fields used by us, the "software" relative error in the calculated wave heights

H_s even in a "perfect" model may comprise about 20% (since $H_s = 4\sqrt{E}$, $\Delta H_s/H_s = \Delta E/2E \approx \Delta W/W$). One can see that this value is close to that obtained in our calculations; i.e., actually, we reached the limit accuracy available at the present-day quality of the wind fields specified.

If we assume that the errors of the buoy measurements of H_s are about 10% [7], the model errors in the wind specifying necessary for the model verification should be less than 10%. This estimate imposes certain requirements on the wind field accuracy used in the model verification. Therefore, further efforts aimed at the model verification and enhancement should deal with wind fields and wave parameters whose accuracies lie within the above-cited limits. Probably, at present, precisely this is the principal requirement that determines the scope of the future improvement of numerical wind wave modeling.

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