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An Extended Verification Technique for Solving Problems of Numerical Modeling of Wind Waves

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Abstract—Based on different modifications of the source function in the WAM(C4) wind-wave model, a large series of verification calculations aimed at increasing the quality of the numerical model (with respect to the parameters of accuracy and performance) is performed. We propose a methodology allowing us to solve the following fundamental and practical problems of numerical modeling: (1) determining the minimum interval of verification of numerical wind-wave models, (2) finding a criterion for choosing the best model out of all models subjected to verification, and (3) formulating the accuracy requirement for specifying the input field necessary for the given accuracy of wind-wave field calculations. Particularly, we have found that (a) the minimum term of verification calculations for numerical wind-wave models is three months; (b) according to our criterion, the proposed modification of the WAM model impartially is "essentially preferable" to the original model; and (c) the relative errors (yielded by the proposed version of the WAM model) in the calculated wave heights ρH_s and average periods ρT_m for different levels of the relative error of the input wind-wave field ρW make it possible to solve the third problem mentioned above.

Key words: wind waves, wave spectra, numerical modeling, forecast, verification.

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1. INTRODUCTION

This study is a natural continuation of the previous two papers [1, 2], which consider a verification technique for the numerical wind-wave model to demonstrate the benefits of a new model-source function proposed earlier in [3]. This technique, which is related to the determination of the accuracy characteristics of the tested model, can be described using the example of wind waves as follows.

Let, in line with [3], the complete spectral model of wind waves be given by the wave-energy balance written as the equation of transfer for the energetic two-dimensional frequency–angle wave spectrum $S \equiv S(\sigma, \theta, \mathbf{x}, t)$. Here, σ and θ are the frequency and direction of propagation of the wave component with the wave vector $\mathbf{k}$, $\mathbf{x} = (x, y)$ is the spatial coordinate of the wave field, and t is time. In the simplest case of deep water and ignoring the influence of currents, that equation has the form

$$\frac{\partial S}{\partial t} + C_{gx}\frac{\partial S}{\partial x} + C_{gy}\frac{\partial S}{\partial y} = F \equiv NL + IN - DIS, \quad (1)$$

where the left-hand side includes the full derivative of a spectrum with respect to time and the right-hand side is the so-called source function F of the wind-wave model. In the framework of the approximations adopted, the source function F consists of three main terms that are parts of the general evolutionary mechanism of wind waves: the nonlinear mechanism of evolution NL, the mechanism by which energy is supplied to waves by wind IN (pumping), and the mechanism of energy loss by waves DIS (dissipation). The physical sense of each of these terms of the source function is well known and has been described in detail (for example, in our papers [3, 4] and other studies [5, 6]). In view of this, hereafter, we will not consider the details of this problem.

The solution method for Eq. (1) is determined by the model mathematics, and its physical content is specified namely by the explicit form of the model source function F (SF). Therefore, any functional change in the mathematical representation of SF terms is equivalent to model modification. The verification technique is used to qualitatively estimate the degree of model validity.

In its turn, the validity of a wind-wave model of form (1) is determined by the set of estimates for deviations of calculated values of wave parameters $P_{num} \equiv P_{num}(\mathbf{x}, t)$ from their observed values $P_{obs} \equiv P_{obs}(\mathbf{x}, t)$. These deviations, determined in one way or another, are normally called (verification) errors of the model. The verification calculations are performed for a specially prepared (in the sense of degree of validity) wind field $\mathbf{W}(\mathbf{x}, t)$ given at a standard level over an average sea level (usually 10 m) and serving as an input signal for the numerical model. As a rule, one uses the wind fields obtained from reanalysis (a description of its specific features can be found, for example, in [7]). The standard verification technique is terminated when a set of estimates of verification errors obtained is accompanied by their analysis. Examples of the application of this technique to the modified WAM [8] and WAVEWATCH [9] models were described in our previous studies [1, 2].

For further discussion, it is important to note that the standard verification technique normally does not try to choose the most accurate model out of those subjected to verification. This problem is of a certain basic and practical interest. However, to this day, no criterion for choosing the best model has yet been formulated.

As part of the solution to such a problem, we introduced the concept of comparative verification in [1, 2], including an additional procedure for comparing errors for two models: new (tested) and well-known (taken to be reference). Here, to complete the solution to this problem, we try to formulate a suitable criterion of choice.

In addition, the standard verification technique does not solve problems of establishing the link between the model accuracy and the accuracy of specifying the input data (wind field).

Therefore, as a continuation of studies [1, 2], in this work we try to extend the application area of the verification technique up to a level allowing us to answer the questions listed above. In this case, the extended comparative verification, starting with a simple technical procedure, grows to the level of methodology for solving a series of scientific and applied problems.

This study has the following objectives:

(1) conduct an extended comparative verification of the original and modified WAM models, as well as perform a comparative analysis of verification errors depending on the time intervals of observation data in use (the so-called verification time);

(2) based on statistical observation data and the results of a comparative verification, formulate a criterion for choosing the most efficient numerical model of wind waves and impartially establish the preference of the original or modified WAM model;

(3) using the example of a modified WAM model, find the dependence of errors in model calculations on errors in the input wind field and on conditions of processing calculation results.

In the course of achieving these objectives, we propose and implement a technology of comparative verification calculations, making it possible to impartially solve the following basic and practically important problems: (1) determining the minimum verification time of arbitrary numerical wind-wave models, (2) finding a criterion for the choice of the best model of all the models subjected to verification, and (3) formulating a requirement for the accuracy of input fields necessary to reach a given calculation accuracy for the field of wind waves.

This methodology can be evidently extended to numerical models of any types and for any phenomena.

2. THE METHOD

2.1. Modified Source Function and Sense of Its Varied Parameters

First of all, based on previous publications [3, 4], we briefly describe the new source function with an additional explanation of the physical sense of its main parameters, the variation of which makes it possible to control the accuracy of wind-field calculations.

2.1.1. To describe the nonlinear mechanism of evolution $NL(S)$ in the new SF, we use a well-known approximation of discrete interactions (DIA) modified in a definite way to enhance its performance.[1] Proposed in our studies [10, 11] and described in detail in [3], this modification does not add a new physics. However, as was shown directly in [1, 2], it allows one to fetch computations by 25–30% without any loss in accuracy only by excluding the spectrum-interpolation procedure used in the standard version of DIA (see [3] or [10] for details). The new version of DIA was called Fast DIA (FDIA).

Finally, in the new SF, the term $NL(S)$ can be symbolically written as

$$NL(S) = C_{NL} NL_{FDIA}(S). \tag{2}$$

In this case, in view of the fact that the calculation procedure $NL_{FDIA}(S)$ is completed on the basis of optimally configuring the interacting quadruple of waves (see [11]), the only adapting parameter of parametrization (2) is the dimensionless coefficient C_{NL}. Its physical sense is evidently the intensity of the term $NL(S)$ of SF. The theoretical estimate for C_{NL}, which, in essence, is a constant of the integration of nonlinear interactions on average, is on the order of 10^4. A more accurate value of C_{NL} is naturally determined as a result of model tuning because it depends on the balance of all SF terms.

2.1.2. The pumping term $IN(S)$ in our SF corresponds to Miles' standard model [12]; i.e., it is determined by a linear function of the wave spectrum:

$$In(S) = C_{IN}\beta(\sigma, \theta, \mathbf{W})\sigma S(\sigma, \theta), \tag{3}$$

[1] The approximation of discrete interactions is the simplest change of the complete six-fold integral of four-wave nonlinear interactions by a term with a specially chosen configuration of the quadruplet of interacting waves (a multidimensional analog of integration "on average").

where the wave-growth increment $\beta(\sigma, \theta, \mathbf{W})$ is parametrized on the basis of the generalized empirical formula

$$\beta = \max\left\{-\beta_{sw}, \left[0.04\left(\frac{u_*\sigma}{g}\right)^2 + 0.00544\frac{u_*\sigma}{g} + 0.000055\right]\cos(\theta - \theta_w) - 0.00031\right\}. \quad (4)$$

In (3) and (4), the following notations are used: $\mathbf{W} = \mathbf{W}(\mathbf{x})$ is the local velocity of wind at a standard level, u_* is the corresponding friction velocity (calculated from W by a special procedure existing in each individual model of wind waves), and θ_w is the direction of local wind.

The main advantages of parametrization (4) are (i) a wide application area with respect to frequency band; (ii) the correspondence of the functional dependence $\beta(u_*)$ to most theoretical calculations; and (iii) the presence of negative values $\beta = -\beta_{sw}$, which describe back energy transfer for wind-passing waves (see [3] for details). Usually, the parameter β_{sw} is taken to have a value "by default" close to theoretical estimates: $\beta_{sw} = 5 \times 10^{-6}$.

This parametrization of $IN(S)$ differs positively from that in the model WAM due to its advantages listed above. However, from the physical point of view, the mechanism by which energy is supplied to waves by wind remains almost the traditional one (if attention is not focused on the introduction of β_{sw}, which is not available in WAM). The value of the main variation parameter C_{IN} determined by the balance of all SF terms is established as a result of the procedure of model tuning (see [3]).

2.1.3. The most radical changes in the new SF are applied to the parametrization of the dissipation mechanism $DIS(S)$, the nature of which has been the least studied both theoretically and experimentally [3–6]. Omitting the details of this problem, which have been described in detail earlier in [3], we merely note that the mechanism of wave-energy dissipation is completely conditioned by the interaction between wave motions and the turbulence of the upper water layer. In its turn, the latter is generated by a great number of physical processes, including different kinds of hydrodynamic instabilities of mechanical motions near the interface. The details of these processes are not significant because, due to their stochastic character, the turbulence of the upper sea layer is determined by the laws of statistical hydromechanics. As a result, the proposed mechanism of wind-wave dissipation has a nature of losses caused by turbulent viscosity; i.e., it allows for a clear physical treatment.

The final expression for the proposed version of $DIS(S)$ is given by the following relations:

$$DIS(\sigma, \theta, S, \mathbf{W}) = C_{dis}c(\sigma, \theta, \sigma_p)\max[\beta_{dis}, \beta(\sigma, \theta, \mathbf{W})]\frac{\sigma^6}{g^2}S^2(\sigma, \theta), \quad (5)$$

where the function $\beta(\sigma, \theta, \mathbf{W})$ is determined by formula (4) and the dimensionless function $c(\sigma, \theta, \sigma_p)$, describing the details of dissipation processes in the area of maximum spectral frequency σ_p, has the form

$$c(\sigma, \theta, \sigma_p) = \max[0, (\sigma - c_p\sigma_p)/\sigma]T(\sigma, \theta, \sigma_p), \quad (6)$$

which includes an "external"-to-spectrum dependence of dissipation on the wave-propagation angle, which is specified as a phenomenological function:

$$T(\sigma, \theta, \sigma_p) = \left\{1 + 4\frac{\sigma}{\sigma_p}\sin^2\left(\frac{\theta - \theta_w}{2}\right)\right\}\max[1, 1 - \cos(\theta - \theta_w)]. \quad (7)$$

The standard notation max[..., ...] means the choice of a maximum of numbers standing in the brackets.

As follows from (5)–(7), the proposed parametrization of DIS involves (along with general physics) two phenomenological effects:

(i) the existence of a nonzero "background" level of wave-energy loss controlled by the parameter β_{dis};

(ii) the possibility of regulating the wave-dissipation rate at frequencies on an order or more than σ_p by varying the values of parameter c_p.

Note that these physically important elements in the parametrization of DIS have not been used earlier by anyone. Finally, taking into account the intensity constants C_{dis}, the new parametrization of DIS has only three varying parameters.

Earlier, to minimize the varying parameters, the values of β_{dis} and c_p were postulated by us to be by default (see [1–3]). However, in this work, along with varying the major turning constant C_{dis}, we also subjected the parameters β_{dis} and c_p, to variation, aiming to determine their actual influence on the accuracy of calculations. Here, we found—and it is important to point out—that the variation of β_{dis} significantly affects the wave-dissipation rate for attenuated (or sharply turned) wind and the variation of c_p has an essential influence both on waves with extreme heights and on the accuracy of a calculation of their average period T_m. The latter, as can be seen from formulas (5) and (6), is conditioned by the choice of the value of c_p on the form and level of high-frequency "tail" of spectrum (see formula (12) for T_m further).

This completes the data on the new SF and its varying parameters needed for further discussion.

2.2. Formulas of Verification Errors

Like earlier in this study, we limit ourselves to calculating only three types of verification errors, assuming that the extension of their number to the standard level of 5–7 characteristics (by the examples described in [13, 14]) is not principal and can be omitted for the aims to be achieved here. Thus, we calculate only the following error types obtained from the example of a generalized characteristic of the wave field P:

• rms error δP, given by the formula

$$\delta P = \left(\frac{1}{N_{obs}} \sum_{\substack{n=1 \\ (P_{obs} > P_{\min})}}^{N_{obs}} [P_{num}(n) - P_{obs}(n)]^2 \right)^{1/2}, \quad (8)$$

• relative rms error ρP, defined as

$$\rho P = \left(\frac{1}{N_{obs}} \sum_{\substack{n=1 \\ (P_{obs} > P_{\min})}}^{N_{obs}} \left(\frac{P_{num}(n) - P_{obs}(n)}{P_{obs}(n)} \right)^2 \right)^{1/2}, \quad (9)$$

• and arithmetic error αP, following from the relation

$$\alpha P = \left(\frac{1}{N_{obs}} \sum_{\substack{n=1 \\ (P_{obs} > P_{\min})}}^{N_{obs}} (P_{num}(n) - P_{obs}(n)) \right). \quad (10)$$

Here, N_{obs} means the number of observations of the characteristic P, which were taken for calculating the location of a buoy at a fixed point $\mathbf{x}$, and the summing is taken with respect to the time series t with index n. The physical sense of definitions (8)–(10) is well known and requires no explanations.

However, a special explanation is required for the peculiarity that, in the error definitions adopted here, the summing is taken only for the values of series at those times n for which the observed values satisfy the condition

$$P_{obs}(n) > P_{\min}. \quad (11)$$

Here, $P_{\min}$ is the preset minimum value of the observed variable, being a threshold below which the value of wave characteristic presents no practical interest. Hereafter, $P_{\min}$ will be called the "limit (or level) of significance" of the wave characteristic P. The meaning of the use of $P_{\min}$ will become clear from a further analysis of the relationships between the errors in the given characteristics of the wind–wave system.

The characteristics (or parameters) of the wind–wave system $P(\mathbf{x}, t)$ are then taken to be significant wave height H_s, as determined from the spectrum by the formula

$$H_s = 4\left(\int S(\sigma, \theta) d\sigma d\theta \right)^{1/2}, \quad (11)$$

the average wave periods T_m, given by

$$T_m = \frac{2\pi \int \sigma^{-1} S(\sigma, \theta) d\sigma d\theta}{\int S(\sigma, \theta) d\sigma d\theta}, \quad (12)$$

and the values of the wind module W at the standard level. In the latter case, the reference parameters were represented by reanalysis data and the observed values are measurement data on buoys.

In initial calculations, the following significance levels $P_{\min}$ were used for the parameters

$$H_{s\,\min} \geq 1 \text{ m}; \quad T_{m\,\min} \geq 1 \text{ s}; \quad W_{\min} \geq 1 \text{ m/s}. \quad (13)$$

Further, we vary the significance levels to solve the problems posed in this work (see Section 4 addressing the results obtained).

2.3. The Data Used and Verification Conditions

The problems posed in this work were solved in the following way.

First, it was necessary to use the most comprehensive and reliable data on wind fields and buoy observations over waves. In this respect, we focused our attention to the modern databases available at NCEP (United States) and ECMRWF (United Kingdom). As a result, we obtained reanalysis data on wind with a resolution of 3 h in time and 1.25×1 degrees in space, as well as wave data from 50 buoys in the North Atlantic (NA) for 2006.[2] After quality control and choice of deepwater areas in NA aimed at the observability of calculation results, 15 buoys were chosen for this study. At this stage of works, this quantity of buoys is well justified.[3]

When choosing the system of wave data to be investigated, we especially choose buoys located in two zones that are highly different by meteorology: the eastern part of NA (buoys around Britain) and the western part of NA (buoys along the North America coast).[4]

Secondly, in this work we take the well-known WAM model as the basis and the same model differing only by the use of a new SF (described in Section 2.1) as the "modified" model. The technique of comparatively verifying different versions of WAM modifications was applied to a great number (40 variants) of variations of the above-mentioned parameters of SF

[2] The author is grateful to Jean Bidlot (ECMRWF) for help in obtaining these data. More comprehensive wind-field data of different origins with different resolutions in time and spaces, as well as with different accuracy, are not yet available.

[3] The use of a larger number of buoys at other observation periods is one aim of the next stage of the study.

[4] To save room, the schematic of buoy allocation is not presented (it can be found in [1, 2]).

terms. On the basis of this set of variants, the optimal choice of parameters of the new SF was determined by the fact that a minimum of the rms error δP (averaged over all buoys) is reached. Thus, first, the influence of the indicated parameters on the model accuracy was established; second, the most efficient SF was chosen. Clearly, such a choice of optimality is of a conditional character, because it depends on the degree of approximation for the absolute minimum of the error, the value of which cannot be known in advance (i.e., in the searching method, this choice is nonunique). Nevertheless, the approach adopted solves the problem posed in this work. Here, it is assumed that, under sufficient calculation statistics, a comparative analysis of the errors that was performed on the results of such calculations yields sufficient grounds for making a decision on the choice of the best model version.

Thirdly, the final version of the modified model was further verified through a calculation of errors with the following changes in the conditions of calculations:

(i) by the time step of the processed data (1- and 3-h data);

(ii) by geographic areas (eastern and western NA);

(iii) by verification times (from 1 to 12 months);

(iv) by the division of the verification time into seasons (summer and winter);

(v) by the significance levels of wave and wind parameters used in calculations of modeling errors.

Below, we present a highly concentrated system analysis of our results.

3. ANALYSIS OF THE RESULTS OBTAINED

3.1. Search for Optimum SF Parameters

The main series of calculations of wave characteristics in NA was performed for different versions of the modified WAM model with variations of the main parameters of the new SF within the following ranges:

$$\begin{gathered} 0.9\times10^4 \le C_{NL} \le 1.5\times10^4; \quad 0.4 \le C_{IN} \le 0.6; \\ 9.0 \le C_{DIS} \le 20.0; \quad 0.1 \le c_p \le 0.7 \end{gathered} \tag{14}$$

for default values of β_{sw} and β_{dis}, (see Section 2.1). Here, as can be easily understood from the nature of nonlinear interactions [4], an increase in C_{NL} leads to increased periods of the spectral peak of waves, and the variation of parameters C_{IN} and C_{DIS} normally provides a corresponding increase or decrease in the wave height $H_s(\mathbf{x}, t)$ at observation points. The combined (and unidirectional) variation of parameters C_{DIS} and c_p makes it possible to vary their average periods $T_m(\mathbf{x}, t)$ supporting a certain level of wave height. Thus, the variations of these parameters allows one to reach some minimization (or optimization) of the buoy-averaged error $\langle\delta H_s\rangle$ in calculating the wave height, which is a key characteristic of the accuracy of the model.[5]

Finally, the resulting optimal values of SF parameters for the new model version, denoted hereafter as NEW, are

$$\begin{gathered} C_{NL} = 1.2\times10^4; \quad C_{IN} = 0.5; \\ C_{DIS} = 12.0; \quad c_p = 0.1, \end{gathered} \tag{15}$$

for default values of β_{sw} and β_{dis},

3.2. Benefits of the NEW Model

The initial estimates for the verification errors determined by formulas (8)–(10) were calculated for the wave parameters H_s, T_m, and wave force W for the values of significance limits given according to relations (13). The comparative verification was performed on the basis of suitable calculations with the original version of WAM.

By analogy with the results already published in [1], for all verification times (from 1 to 12 months), the direct benefits of the NEW version (when compared to the original WAM version) were confirmed with respect to both the accuracy and speed of the calculation.[6] It has been established that the verification errors δH_s and δT_m are almost independent of the time step Δt_{dat} used for data: $\Delta t_{dat} = 1$ h or $\Delta t_{dat} = 3$ h. The first value of Δt_{dat} corresponds to the standard time step of data registered at buoy stations, and the second corresponds to the time step of the initial wind field. Note that, in this case, no spatial–temporal averaging was used to ensure that the statistical pattern of comparison results is not distorted.

The comparative characteristics of accuracy for the NEW and original WAM (hereafter, simply WAM) models for 15 buoys are shown in Table 1 (the verification period is January–March, 2006, and the time step of data is $\Delta t_{dat} = 3$ h). The first two columns of this table testify that the NEW model is advantageous for an overwhelming number of buoy-location points for the characteristics of both δH_s, and δT_m. Here it is interesting to note that the ratio of relative errors ρH_s and ρT_m for both model versions is qualitatively consistent with the ratio of δH_s and δT_m; the ratio of arithmetic errors αH_s and αT_m for both versions is less regular.

The existing losses of accuracy of NEW when compared with the original WAM for a number of buoys

[5] The major significance of the wave height H_s is conditioned by the direct relation of H_s with the wave energy according to formula (11), as well as by the fact that it can be directly observed.

[6] Hereafter, the issue of calculation performance will not be discussed because it has been described in detail in [1, 2] and because of the unambiguous computational speedup through the use of the FDIA approximation in parametrizing the term $NL(S)$.

Table 1. Comparison of verification errors for two versions of the WAM model (data from 15 buoys in NA and for the period of January to March, 2006)

Number of buoys/Type of model	Error types						Gain in accuracy	
	δH_s, m	αH_s, m	ρH_s, %	δT_m, s	αT_m, s	ρT_m, %	$\frac{(\delta H_s)_{\rm wam}}{(\delta H_s)_{\rm new}}$	$\frac{(\delta T_m)_{\rm wam}}{(\delta T_m)_{\rm new}}$
41001/WAM	0.67	–0.48	20	1.12	0.98	19	1.31	1.37
/NEW	0.51	–0.25	17	0.82	0.21	14		
41002/WAM	0.47	–0.27	16	1.24	1.10	22	1.17	1.28
/NEW	0.40	–0.13	17	0.97	0.43	18		
41010/WAM	0.42	–0.27	18	1.47	1.30	29	1.07	1.12
/NEW	0.39	–0.29	20	1.31	0.85	28		
44004/WAM	0.62	–0.35	19	1.35	1.17	24	1.15	1.29
/NEW	0.54	–0.08	21	1.05	0.44	19		
44008/WAM	0.88	–0.70	32	0.95	0.64	18	1.69	**0.87**
/NEW	0.52	–0.28	22	1.09	0.60	21		
44011/WAM	0.61	–0.42	20	1.57	1.37	27	1.42	1.45
/NEW	0.43	–0.12	16	1.08	0.66	19		
44137/WAM	0.43	–0.10	16	1.44	1.25	22	1.00	1.58
/NEW	0.43	0.17	15	0.91	0.44	15		
44138/WAM	0.56	0.07	21	2.12	1.91	31	0.98	1.88
/NEW	0.57	0.27	18	1.13	0.69	17		
44139/WAM	0.45	–0.02	17	2.03	1.89	32	**0.85**	1.60
/NEW	0.53	0.19	19	1.27	0.96	22		
44141/WAM	0.42	0.12	18	1.77	1.63	26	**0.70**	1.81
/NEW	0.60	0.34	21	0.98	0.62	16		
62029/WAM	0.54	–0.09	15	2.44	2.26	34	1.02	1.71
/NEW	0.53	–0.22	13	1.43	1.06	21		
62081/WAM	0.52	–0.03	17	2.38	2.22	33	1.16	1.79
/NEW	0.45	–0.11	15	1.33	1.01	20		
62105/WAM	0.50	–0.09	13	2.34	2.18	33	1.00	1.77
/NEW	0.50	–0.15	13	1.32	0.99	20		
62108/WAM	0.66	–0.28	14	2.07	1.92	28	1.18	2.20
/NEW	0.56	–0.18	12	0.94	0.58	13		
64046/WAM	0.54	–0.16	13	2.09	1.93	29	**0.96**	1.77
/NEW	0.56	–0.15	14	1.18	0.82	18		

Note: Boldface values correspond to cases of loss in accuracy for the version of NEW model.

are caused primarily by random factors stemming from the randomness of wind and wave fields rather than by the physics of models and their optimization levels. Also, systematic errors of measurements are possible for a number of buoys. However, a detailed discussion of this issue is beyond the scope of this study.

The errors averaged over 15 buoys for the original WAM model have the values (see Table 1)

$$\langle \delta H_s \rangle_{\rm WAM} = 0.55 \text{ m}; \quad \langle \delta T_m \rangle_{\rm WAM} = 1.76 \text{ s}, \tag{16}$$

while, for the version of NEW model,

$$\langle \delta H_s \rangle_{\rm NEW} = 0.50 \text{ m}; \quad \langle \delta T_m \rangle_{\rm NEW} = 1.12 \text{ s}. \tag{17}$$

The values of $\langle \delta H_s \rangle$, $\langle \delta T_m \rangle$ by themselves are interesting as key characteristics of the accuracy of a model. Along with this, when a criterion for choosing a preferential model is available, it is their values that become decisive. This issue is considered in detail in the following subsection.

Here, it makes sense to note that the comparison of averages (16) and (17) with the analogous results obtained earlier [1] for a geographical grid of wind and wave fields of 2.5° × 2.5° with the same time step for wind Δt_{dat} = 3 h speaks to an essential (by around 30%) decrease in the calculation errors $\langle \delta H_s \rangle$ and

Table 2. Ratios of verification errors for two versions of the WAM model for 1 and 3 winter months of 2006

Number of buoys	WAM			NEW			$\frac{(\delta H_s)_{\text{WAM}}}{(\delta H_s)_{\text{NEW}}}$
	δH_s, m	αH_s, m	ρH_s, %	δH_s, m	αH_s, m	ρH_s, %	
Eastern part of NA							
62029	0.62/0.54	−0.15/−0.09	18/15	0.59/0.53	−0.20/−0.22	12/13	1.05/1.02
62081	0.60/0.52	−0.06/−0.03	16/17	0.41/0.45	−0.02/−0.11	10/15	1.46/1.16
62105	0.56/0.50	−0.22/−0.09	13/13	0.48/0.50	−0.06/−0.13	11/15	1.17/1.00
62108	0.69/0.66	−0.23/−0.28	13/14	0.50/0.56	0.11/−0.15	10/13	1.38/1.18
64046	0.62/0.54	−0.26/−0.16	13/13	0.61/0.56	−0.01/−0.15	13/14	1.01/0.96
Western part of NA							
41001	0.70/0.67	−0.46/−0.48	19/20	0.48/0.51	−0.22/−0.25	15/17	1.46/1.31
41002	0.50/0.47	−0.28/−0.27	16/16	0.42/0.40	−0.15/−0.13	19/17	1.19/1.17
41010	0.40/0.42	−0.27/−0.27	16/18	0.41/0.39	−0.28/−0.29	19/20	0.98/1.08
44004	0.69/0.62	−0.34/−0.35	20/19	0.61/0.54	−0.10/−0.08	24/21	1.13/1.15
44008	0.87/0.88	−0.64/−0.70	29/32	0.55/0.52	−0.23/−0.28	24/22	1.58/1.69
44011	0.62/0.61	−0.38/−0.42	18/20	0.46/0.43	0.00/−0.12	18/16	1.35/1.42
44137	0.42/0.43	−0.15/−0.10	14/16	0.45/0.43	0.19/0.17	16/15	0.93/1.00
44138	0.56/0.56	0.11/0.07	19/21	0.63/0.57	0.41/0.27	20/18	0.89/0.98
44139	0.46/0.45	−0.97/−0.02	15/17	0.53/0.53	0.29/0.19	18/19	**0.87/0.85**
44141	0.38/0.42	0.03/0.12	15/18	0.60/0.60	0.39/0.34	21/21	**0.63/0.70**

Note: The "/" sign separates the values related to the one- and three months of the verification period, respectively. Boldface values correspond to buoys for which the NEW model for the verification period of 3 months falls short in accuracy by more than 5%.

$\langle \delta T_m \rangle$ with a decrease in the spatial step of wind (from 2.5° to 1.25°). This fact can be easily explained, and it points out the importance of the use of wind fields with a maximum-possible spatial and temporal resolution. Evidently, an increase in the calculation accuracy for the wind field is conditioned by both the increased accuracy the numerical scheme for solving evolutionary equation (1), and the possibly increased accuracy of the input wind field. As was noted in Footnote 2, the role of the latter factor currently cannot be checked directly.

3.3. Spatial and Temporal Variability of Verification Errors

Let us consider the question of influence of the verification times (i.e., the time periods of measurement data in use) and the geographical distribution of buoys on the numerical error of model verification. To do this, we use the example of estimates of δH_s and ρH_s to compare the verification errors in both model versions for 1, 3, and 6 winter months in 2006 and for 15 buoys in NA. It is convenient to make this comparison in two stages.

According to Table 2, when comparing the errors at the scales of 1 and 3 months, both model versions show a quasi-chaotic spatial distribution of error variations in the range between 10 and 20%.

When the verification period is increased from 1 to 3 months, the original WAM model in the eastern NA unambiguously shows a decline in the errors δH_s with a preservation of the variation level of the above-mentioned level. However, for the western part of NA, there are cases of increased errors. The variations of relative errors ρH_s are more chaotic with respect to buoy location and oscillate within 10%.

For the same change of verification periods, the NEW model for the eastern part of NA yields no unambiguous change in errors δH_s, showing their variation to be within 10%; however, for the western part of NA, there is normally a decline in the level of errors δH_s within the same range. The spatial scatter of ρH_s in the NEW model is irregular and has an average order of around 10%.

Note that the minimal errors δH_s don't always correspond to the minimal values ρH_s. In the western part of NA, the values of ρH_s, are normally higher than in the eastern part. It seems that this is related to the relevant distribution of wind errors (see Subsection 3.5).

In general, at all verification periods, the ratio of both error types points to the preference of the NEW model, especially in the eastern part of NA, which is clearly demonstrated in the right column of Table 2 (see Note). Therefore, in view of the previous demonstrations of benefits of the NEW version when compared to the original WAM (Table 1 and paper [1]), we will not discuss a further comparison of model accuracies and all the subsequent estimates will refer only to the NEW version.

Table 3. Ratios of verification errors for two versions of the WAM model in 6 summer months, 6 winter months, and 3 winter months in 2006

Number of buoys	NEW model				Wind characteristics	
	δH_s, m	ρH_s, %	δT_m, s	ρT_m, %	δW, m/s	ρW, %
Eastern part of NA						
62029	0.47/0.52/0.53	19/13/13	1.12/1.36/1.43	19/20/21	1.46/2.04/1.76	25/26/25
62081	0.43/0.49/0.45	16/14/15	0.97/1.24/1.33	16/18/20	1.68/2.12/2.21	27/28/30
62105	0.44/0.56/0.50	17/13/13	1.00/1.16/1.32	17/17/20	1.94/2.66/2.66	29/48/48
62108	0.46/0.60/0.56	17/13/12	0.82/0.90/0.94	13/12/13	2.15/2.53/2.52	37/31/31
64046	0.49/0.56/0.56	21/14/14	0.97/1.10/1.18	17/16/18	1.46/1.70/1.66	25/24/24
Western part of NA						
41001	0.50/0.50/0.51	28/17/17	0.68/0.80/0.82	12/14/14	1.63/2.08/2.04	32/31/30
41002	0.51/0.40/0.40	31/20/17	0.96/0.94/0.97	17/18/18	1.77/1.79/1.94	42/33/35
41010	0.63/0.44/0.39	37/24/20	1.45/1.33/1.31	30/28/28	1.20/1.29/1.26	27/25/23
44004	0.44/0.52/0.54	22/20/21	1.08/1.00/1.05	20/19/19	1.69/1.92/1.92	34/34/31
44008	0.44/0.53/0.52	24/22/22	0.85/1.03/1.09	16/21/21	2.51/2.26/2.29	60/44/42
44011	0.41/0.44/0.43	20/17/16	0.94/1.02/1.08	17/19/19	2.17/2.10/2.05	48/37/33
44137	0.36/0.46/0.43	19/18/15	0.71/0.91/0.91	12/16/15	1.89/2.06/2.07	39/34/33
44138	0.55/0.49/0.57	24/17/18	0.96/1.20/1.13	17/20/17	1.55/1.85/196	28/31/33
44139	0.40/0.49/0.53	19/19/19	0.85/1.12/1.27	15/19/22	1.72/1.77/1.84	35/40/31
44141	0.40/0.59/0.60	18/22/21	0.70/0.98/0.98	12/16/16	1.70/2.11/2.26	34/33/36

Note: The "/" signs separate the values related to the 6 summer, 6 winter, and 3 winter months of the verification period, respectively.

Further extending the verification period up to 6 months (limited by the length of winter–summer seasons) leads to an inessential decrease in variations of δH_s, ρH_s, as well as δT_m and ρT_m (Table 3). Remaining differently directed, the variations of all error types decrease up to 3–5% on average for all buoys. In this case, no direct dependence of variations of both error types on the geographical location of buoys is observed. However, a seasonal variability is observed, which is discussed later in Subsection 3.5.

The above discussion yields two important conclusions of this part of the study needed for the development of practical recommendations on the choice of an optimal numerical model of wind waves.

The first conclusion is that the characteristic verification period required for a reliable estimation of the numerical error of the model constitutes 3 to 6 months. Therefore, the minimal period of verification of the numerical model of wind waves must be around 3 months.

The second conclusion is that the statistical (spatial and temporal) error of the estimate for the verification error $\Delta_{\delta P}$ constitutes some 5%. It seems that this value is determined by the statistical variability of the wind field and depends insignificantly on its accuracy or the model accuracy. Clearly, these issues require additional investigations.

In turn, the verification errors δP and ρP themselves at the modern level of wind-wave modeling essentially increase the error $\Delta_{\delta P}$ and, apparently, are controlled substantially by the accuracy of wind specification (see below).

The second conclusion yields the following apparent corollary: The differences in errors of verification calculations obtained for any of the versions of numerical wind-wave models and being no more than 5% should be regarded as undistinguished, and the corresponding models should be regarded as having similar accuracy.[7]

Here it is important to note that the increase in verification periods is limited by the change of seasons, and the seasonal variability of verification errors needs special consideration. In addition, it is equally important to answer the question about the interannual variability of verification errors. Nevertheless, leaving these questions to be considered later, we can now turn to the formulation of a criterion for the choice of the most accurate model.

3.4. Criterion for the Choice of the Best Model

The values of verification errors $\Delta_{\delta P}$ and the character of their spatial and temporal distribution found above make it possible to suggest that the value of 5% can be regarded as the maximum accessible lower boundary for variations in the errors of numerical cal-

[7] Because the lower boundary of the variation in verification errors is determined by the statistical nature of the phenomena under consideration (wind and wind waves), it can be supposed that the minimal value of variations of $\Delta_{\delta P}$ of 5% will be observed for all types of wind-wave models, regardless of their structural peculiarities (see the model classification issues in [4–6]).

culations for both wave heights H_s, and average period T_m. In other words, the value 5% is the minimal error in calculating verification errors, which is conditioned by the randomness of the process of wave generation.

At the same time, the verification errors themselves far from reach this limit. Indeed, for example, for the NEW model in 6 winter months, these errors (with significant variations from one buoy to another) are on the order of $\delta H_s \cong 0.4$–0.5 m for the wave height under the average values of the relative error $\rho H_s \cong 15$–20%. For the wave periods, the same errors have values $\delta T_m \cong 1$ s and $\rho T_m \cong 15$–20%, respectively.

However, it should be noted that these estimates are valid only for the earlier chosen significance levels of empirical data (13). The influence of these levels on verification errors is discussed below. However, forestalling, we note that the choice of significance levels insignificantly affect the order of these values.

To solve the question of the criterion of choosing the best model, we require accurate observation data. Based on the data in the literature, one can assume that the minimal (constructive) relative error of buoy data constitutes some 5–7% by the significant wave height H_s and the same value by their average period T_m [13–15]. Because the empirical error of observations is considerably lower than the verification errors and almost coincides with the lower limit of their variations $\Delta_{\delta P}$,, the criterion of choice of the preferential model can be formulated as follows: it should be accepted that the best of the two tested models (with respect to quality of indicator P) is the one with an average value of the error $\langle \delta P \rangle$ (for a representative set of observation data and input wind data) lowest among the models and differing from the maximum value $\langle \delta P \rangle$ by more than 5%.

If this criterion is satisfied with respect to a series of quality indicators, including the most important characteristics of the reference wave field (significant height, major and average periods, general direction of waves, and speed of calculations), one can suggest that the advantage of the model is of an essential (absolute, on its peak) character. When the criterion is satisfied only for a small number of quality indicators, one should mention the degree of relativity of the essential advantage.

To make this criterion more detailed, one naturally should clearly determine the representative set of observation data; concretize the significance levels; and, possibly, indicate the quality of the input wind field. In this study we assume that this set consists of the above-mentioned 15 buoys in NA, the significance levels are given by conditions (13), and the input wind is specified and corresponds to the reanalysis level. Further investigations would demonstrate that this choice is sufficient or should be extended.

Nevertheless, according to this criterion and the database considered, we can suggest that the version of the NEW model proposed by us is impartially "essentially advantageous" over the original WAM model (with respect to three quality indicators: the accuracy of calculations of δH_s, δT_m, and the speed of calculations).

3.5. Seasonal and Geographical Variability of Verification Errors

The seasonal and geographical variability of verification errors are interesting both by themselves and in the sense of searching for the dependence between the errors in wave characteristics and errors in the input wave (a link between input–output errors). Based on the values of significance levels adopted in line with relations (13), we consider the first aspect of this problem.

The results of comparisons between verification errors for 6 winter (January–March and October–December) and 6 summer (April–September) months of 2006 are shown in Table 3. According to this table, for the winter period, the errors δH_s, are normally 30% higher than for the summer period, while the errors ρH_s, conversely, are 30–40% lower. Here, both types of errors for average wave periods (δT_m and ρT_m) in winter are almost always 10–20% higher. The geographical variability of these errors is also rather significant.

These results can be put most simply as follows. If we make the apparent supposition that the wave energetics over NA in the winter period is higher than in the summer period, we can easily suggest that the winter situations often have more extremely high wave characteristics than in summer. In this case, the verification errors δH_s must increase (since the "proper" model always shows a downward bias for the extreme waves due to its inertial feature) and the relative errors ρH_s must decrease (which follows from definition (9)). In this case, the growth of errors δT_m in the winter period can evidently be connected only with the growth in the role of swell, while the growth in ρT_m with the essential dynamics of wave periods is caused by strong wind inhomogeneity.

However, an addition to the above discussion, it should be taken into account that the seasonal–geographical variability of errors is highly influenced by the variability of errors in the input wind field. Here, it is natural to search for dependences between relative input–output errors rather than between their dimensional analogs.

To systematize the results and obtain dependences of verification errors on errors of input wind, we analyze their relationships using the example of relative errors. Particularly, using the results shown in Table 3, one can obtain the following spatial–seasonal rms distributions.

For winter in the eastern part of NA, the values averaged over the area are

$$\rho H_s = 13.4\%, \quad \rho T_m = 16.6\%, \quad \rho W = 31.4\%, \quad (18)$$

for the western part of NA, they are

$$\rho H_s = 19.6\%, \quad \rho T_m = 19.0\%, \quad \rho W = 33.2\%. \quad (19)$$

The corresponding indicators for the summer period in the eastern part of NA are

$$\rho H_s = 18.0\%, \quad \rho T_m = 16.4\%, \quad \rho W = 28.6\%, \quad (20)$$

for the western part of NA, they are

$$\rho H_s = 24.2\%, \quad \rho T_m = 16.8\%, \quad \rho W = 37.9\%. \quad (21)$$

In most of these cases, the variations in errors significantly exceed the limits of the lower boundary of the error $\Delta_{\delta P} = 5\%$; i.e., they are statistically significant. Consequently, the resulting estimates for the seasonal and geographical variability of errors require some interpretation.

As can be seen from relations (18)–(21), for the eastern and western areas, one can note a unique "direct" tendency of the relations of relative errors for wave heights and periods from those for the wind. However, the proportions between errors are essentially "noised." The latter seems largely to be caused by sampling variability. The dependences of proportionality types can be easily seen separately: for the winter period, there are positive correlations in the dependencies of $\rho H_s(\rho W)$ and $\rho T_m(\rho W)$, in summer, they are only for $\rho H_s(\rho W)$. However, compared with the seasonal data, the expected (quasilinear) relations are "noised."

It is clear that one of the reasons for this noise is the inadequate choice of significance levels $P_{\min}$, used to calculate the errors in relations (8)–(10), which are adopted to calculate the verification errors in question. Indeed, it is rather apparent that the decline in significance levels immediately leads to increased values of relative errors (see formula (9)), which is most noticeable during weak hydrodynamic activity. Therefore, one needs to suitably choose more reasonable significance levels for the heights, periods, and wind force in order to obtain more stable (and, consequently, more realistic) error relations. This question and the determination of dependences of verification errors on errors in input data will be addressed in the next section.

4. RELATIONS OF VERIFICATION ERRORS AND THE ROLE OF SIGNIFICANCE LEVELS

First of all, we perform an analytical study. To this end, with some degree of justification, we can use both empirical laws of the dependence of dimensionless wave energy $\tilde{E} = Eg^2/W^4$ and the dimensionless frequency of the wave spectrum peak $\tilde{\omega}_p = \omega_p W/g$ on their dimensionless fetch $\tilde{X} = Xg/W^2$, which are known for conditions of ideal wave generation [5, 6], and fixed values of $\tilde{E}$ and $\tilde{\omega}_p$, which are valid for a fully developed sea.

The empirical laws of wave growth (while rounding numerical parameters in formulas) are given by

$$\tilde{E}(\tilde{X}) = 5 \times 10^{-7}\tilde{X}, \qquad \tilde{\sigma}_p(\tilde{X}) = 14\tilde{X}^{-0.3}, \qquad (22)$$

which are true at scales $\tilde{X} \leq 10^4$ for dimensionless times of wave development $\tilde{T} = \tan/W \geq 10^4$ [5, 6]. The case of a maximally developed wave is fulfilled for dimensionless speedups $\tilde{X} > 3 \times 10^4$ and times $\tilde{T} > 3 \times 10^4$. For a wind W on the order of 10 m/s, the given boundary values of $\tilde{X}$ and $\tilde{T}$ correspond to speedup scales on the order of 100 km and times on the order of 3 h. Therefore, for a low variability of the synoptic wave W considered by us for the given scales, it will be more reasonable to use only the second of the given possibilities. Otherwise, one should use dependence (22).

Like in [15], we use formulas for fixed values of the characteristics of a maximally developed wave in this work, for which (based on the estimates in [5]) the following relations can be used:

$$\tilde{E} \cong 4 \times 10^{-3} \quad \text{and} \quad \tilde{\omega}_p \cong 0.8. \qquad (23)$$

It follows from (23), with account for the definitions

$$H_S = 4\sqrt{E} \quad \text{and} \quad T_m \cong 0.8 \times 2\pi/\omega_p, \qquad (24)$$

after turning to dimensional quantities, and by varying the final equations, we can easily obtain the following relations:

$$\rho H_S \cong 2\rho W; \quad \rho T_m \cong \rho W. \qquad (25)$$

Similarly, it follows from (22) that

$$\rho H_S \cong \rho W; \quad \rho T_m \cong 0.4\rho W. \qquad (26)$$

Thus, on the basis of elementary theoretical estimates, in verification problems, one can expect that the relative errors are represented by quasilinear relations with proportions close to relations (25) and (26). The most essential feature of these relations is that the relative error for the average period ρT_m, is less than that for the significant wave height ρH_S (which is conditioned by a weaker dependence of ω_p on W). Let us try to reveal (25)- and (26)-type relations in our calculations.

In the general case, this can be achieved by analyzing the following variants.

(1) The use of input data on wind from very different sources, which, due to different spatial and temporal resolutions, can provide different relative errors in the wind-field specification. In this case it will suffice simply to compare the average (in any part of the basin) values of relative errors obtained for any verification period. The shortcoming of this approach is that many calculations are required and different sources of global wind fields are available. Because of

the factors mentioned in Footnote 2, we cannot currently use this approach

(2) Because the wind dynamics varies with seasons and differs by geographical areas, one can suppose that the accuracy of the wind fields likewise differs by seasons and oceanic regions. In this case it is initially allowed to compare the relative errors only for a single annual calculation averaged over either seasons or oceanic regions. The apparent advantages of this variant are its suitability and implementability for the minimally required statistics of comparisons.

(3) If the second variant cannot be implemented successfully, it can be replaced by similar calculations but only for the relative errors averaged over months, or one can search for an rms linear regression of error relations over all the buoys. As essentially the development of the second variant, this approach is more complicated, but it enhances the comparison statistics by several times. It can be used in further investigations.

Because the second variant of analysis is the simplest and most accessible, we consider at first the results of its implementation. It is these results that are represented above by estimates (18)–(21).

As was indicated above, the estimates obtained even for average errors are far distant from the expected relations (25) and (26). The most significant inconsistency is that the average relative error for wave heights ρH_s never exceeds the relative error for wind ρW, which is required by (25), and does not even approach to it in line with (26). In addition, the relative error for the average period ρT_m is evidently far from the expected theoretical relation

$$\rho T_m \cong 0.5\rho H_s. \qquad (27)$$

One of the variants of resolving this inconsistency (see Section 3.5) is to eliminate the methodical noise in estimates of verification errors, which are carried out by varying the significance levels $P_{\min}$ of the system elements H_s, T_m, and W. We try to implement this variant in the following way.

Following the recommendations by the hydrometeorological service on choosing the heights and periods for forecast problems [16], one should change the relevant significance levels in the direction of their growth. For example, for heights H_s, according to directions of [16], it makes sense to use 2 m as the lower significance level H_s and $W = 5$ m/s for the wind velocity. Then, in view of definitions (24), for the simplest form of a Pearson–Moskowitz spectrum [5, 6], the corresponding value of T_m is about 7 s.

In line with the objective posed above, for the same calculation data on waves and input data on wind, we reestimated the relative errors ρH_s, ρT_m, and ρW for the following new values of significance levels

$$H_s \geq 2 \text{ m}, \quad T_m \geq 7 \text{ s}, \quad W \geq 5 \text{ m/s}. \qquad (28)$$

Then, we use the technique of averaging relative errors over regions and seasons similar to those described above. The calculation results are as follows.

For winter, in the eastern part of NA, the area-averaged values are

$$\rho H_s = 13.0\%, \quad \rho T_m = 12.0\%, \quad \rho W = 23.4\%, \qquad (29)$$

and, in the western part of NA, they are

$$\rho H_s = 17.4\%, \quad \rho T_m = 11.0\%, \quad \rho W = 22.5\%. \qquad (30)$$

The corresponding summer values in the eastern part of NA are

$$\rho H_s = 16.6\%, \quad \rho T_m = 10.8\%, \quad \rho W = 21.4\%, \qquad (31)$$

and, in the western part of NA, they are

$$\rho H_s = 21.3\%, \quad \rho T_m = 14.7\%, \quad \rho W = 24.0\%. \qquad (32)$$

Relations (29)–(31) yield the fact that the values of ρW become almost equal with one another both in regards to geographical areas and seasons. The same is true for errors ρT_m. These results are rather plausible if we assume a spatial and temporal homogeneity for the error of the given wind field. Note that, due to a changed significance level, the values of errors ρW and ρT_m were changed so that the new relations $\rho T_m(\rho W)$ are well suited into theoretical relation (26) for errors of periods. Furthermore, in most cases, the theoretical relation $\rho T_m(\rho H_s)$ of form (27) is also present. However, the errors ρH_s that are most important for practice turned out to be more conservative. Finally, the theoretical relation $\rho H_s(\rho W)$, following from (26) or (27), is not present at all.

One constant feature of all the resulting relations is that the value of ρT_m is smaller than ρH_s and the relative error of wind ρW is constantly higher than that of waves ρH_s. The first of the relations is rather conceivable from the theoretical considerations mentioned above. Therefore, for practical purposes, one can take as a working relation

$$\rho T_m \cong 0.5\rho W, \qquad (33)$$

which is close to the analogous theoretical relation following from (26).

However, the empirical relation for errors $\rho H_s(\rho W)$ that was obtained in our calculations remains unclear. Additional variations of $H_{s\min}$ towards its decrease down to 0.5 m or increase up to 2.5 m have little effect on the result for ρH_s. The effect of varying $W_{\min}$ up to 7 m/s on the decrease of ρW. is equally small. Particularly, the theoretically predicted condition $\rho H_s \geq \rho W$ in our calculations was never fulfilled. In order to completely understand, we note that stronger variations of $W_{\min}$ and $H_{s\min}$ are motivated neither physically nor practically and, therefore, are not discussed here.

Apparently, the relations of relative errors $\rho H_s(\rho W)$ obtained in our calculations cannot be theoretically justified from the above-mentioned consideration due to the fact that the theoretical assumptions adopted are extremely simple. Indeed, in our opinion, the satisfactory agreement between the simple theory and empirical estimates for the relation $\rho T_m(\rho W)$, is largely caused by the decisive role that the nonlinear evolution mechanism plays in the formation of the frequency structure of the wave spectrum. As to the amplitude of frequency components of the spectrum, the above discussion in Section 2.1 has already revealed that they are more subjected to influences of the pumping and dissipation mechanism (see [3–6] for more details on the role of evolution mechanisms). Therefore, at the given stage of investigations, we have to be content with results (29)–(32).

Nevertheless, by generalizing relations (29)–(32) in determining the relation $\rho H_s(\rho W)$, we can recommend for practical purposes a synthetic variant of the relation $\rho H_s(\rho W)$ of the form

$$\rho H_s \cong 0.7\rho W, \tag{34}$$

which is acceptable with an accuracy on the order of 10–15%. Along with dependence (33), relation (34) can be used for a qualitative determination of the initial accuracy of input wind, which is necessary for forecasting waves of the given accuracy.

Naturally, relations (33) and (34) are valid only for the considered version of the wave model. For any other models, one needs to search for analogs of such relations with the help of the technique used here.

5. CONCLUSIONS

We can summarize that this study, on the basis verification calculations for the modified model WAM(C4), has formulated and solved the following scientific and practical problems.

First, the minimum verification period was found to be around 3 months. In this case, the estimate for the verification error is almost independent of the data time steps Δt_{dat} in the range from 1 to 3 h, and the minimum level of variation in verification errors, which are conditioned by the change in its periods, is on the order of 5%.

Second, we formulated a criterion for choosing the best (or preferential) model out of two (or more) models subjected to verification.

The proposed criterion was extended to the classification with respect to the degrees of preference with account for the number of quality indicators. Without changing the essence of the criterion, the latter can be detailed by using additional corrections for its inherent conceptions.

According to the criterion adopted, the given version of the modified WAM model is impartially essentially preferable with respect to three quality parameters: accuracies in calculating δH_s, δT_m, and performance rates.

Third, we investigated the role of significance levels used in calculating the verification errors, which made it possible to obtain empirical dependences of the relative verification errors of wave characteristics on relative errors of the input wind field.

For the modified WAM model, the relations suitable for practical purposes with an error of 10–15% are expressed as formulas (33) and (34). However, for each specific model, these relations need be found independently, following the technique proposed in this study.

Here, it is important to note that the proposed technique, like any formalized procedure, is of a universal character; i.e., it is suitable for solving similar problems for any types of models and for any physical processes and phenomena.

Along with this, it should be recognized that extending the observation periods and geography of empirical data, as well as the use of additional (ever more reliable) sources of the wind field, can be very expedient for further advancement in obtaining more detailed relations and increasing the accuracy of numerical wind-wave models.

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