New approach to wave weather scenarios modelling.

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Abstract

In the paper problems of wave climate description and modelling are considered. Wave climate is considered as ensemble of conditions of spatio-temporal wave fields characterized by frequency-directional spectra. Such approach with reference to shipbuilding is caused by expansion of the nomenclature of characteristics of wave and a wind, which are necessary for construction and operation of engineering offshore constructions, and operation of ships. Using of expanded set of wave and wind characteristics takes possibility to introduce term "scenario" of wave weather much more correctly and to use it for estimation of navigation safety.

1. Introduction

Initially concept of "scenario" of wave weather was associated with ideas of "mission" or "assumed situations". First such approach was suggested by N.B.Sevastianov in the field of stability in the beginning of 60s [1]. One of the main ideas proposed by N.B.Sevastianov was assumption that the uncountable infinite set of situations may be substituted with sufficient accuracy by the countable and finite sets of discrete situations. Investigation of each element from such set and consideration of each situation in integral estimation with correspondent weight give possibility, as a result, to calculate risk function with the help of full probability formula [2].

Thus reference of assumed situations to some patterns is an important procedure of risk assessment. Considered vector of assumed situations, in which each element is a set of situation parameters, includes both parameters of ship and characteristics of wind and wave excitations. Characteristic set is defined by state-of-the-art of method applied for assumed situations investigation. Problem of involvement of new knowledge about waves, their spectrum, variability, alternation of storms and slack sea arises with methods accuracy improvement.

As was mentioned another approach to considered problem is related with "mission" concept. In 80s some authors proposed to consider ship's ability to carry posed task from the complex point of view including seaworthiness, region of operation, etc. Traditional consideration of only evident extreme stormy situations conditions using of simple approximate expressions for waves spectral density. It restricts shipbuilders' requirements down to knowledge of wave height (h_s) or set ($h_s, \bar{\tau}$) [3,5,etc.]. Neither complex sea, nor storm duration or character of alternation of bad and good weather are not explicitly used in applied methods for risk estimation. Information about geographic region where ship will operate is rarely used for risk estimation (see, for example [4]). Static character of considered phenomena a priori excludes concept of representative voyage, assumed trip, and operation scenario. We can improve risk estimation method if additional parameters characterising waves in assumed situations (different wave systems, wave directions for considered region) are taken into account. But lack of situation evolution in computational method inevitably makes it inexact.

The author in co-authorship with scientists in oceanology field has considered such methods in a series of papers [6-14].

2. Climatic wave spectra. Wave climate.

Development and perfection of methods of wave measurements (e.g. ocean weather ships, buoys, platforms, etc.) allow one to gather hundreds [15] or even thousands [16,17] of wave spectrum in separate points. It takes possibility to introduce new conception of "climatic wave spectre". Initially it was proposed at the XVIII IMO Assembly (1993) as "A wave spectrum which results from averaging the energy density ordinates of a number of measured wave spectra. It is determined for specified significant wave height class intervals, typically 1 meter". At the same time at this Assembly wave climate was defined: A seaway characterization determined primarily from climatic wave spectra obtained at a particular geographic location. It is characterized by parametric and other properties of the local climatic wave spectra and by the associated probability density distribution of significant wave height.

However, the problem of climatic wave spectra calculation is still open because operation of averaging is acceptable only for physical homogeneous phenomena. It involves necessity of climatic wave spectra classification. So Backly proposed to classify wave spectra in formal way. He divided all measured spectra into classes with different significant wave height. Then he averaged them in each class at each frequency [16,17]. However, wind waves of the same height could result from various weather conditions (rising sea, decaying wind waves, swell, etc.). They are characterised by different spectra. We cannot consider introduced terms as settled because some terms used in definitions are not defined. So definition of climatic wave spectrum is acceptable if we shall keep in mind during averaging procedure probabilities of wave making conditions corresponding to different kinds of spectra (i.e. wind speed, duration, fetch, etc.) [10].

Let us consider example of wind wave spectrum variations during a storm passage.

Fig. 1 shows an example of variation of frequency spectrum $S(\omega,t)$ at a point located in the North Atlantic as measured by RV "Weather Reporter" of the UK from 15th to 19th December of 1959 [18]. The upper panel of the figure also shows data on wind speed u, wave height variance D_ζ, and mean wave period τ. Wind strengthening up to 30 knots was taking place from 6 to 18h of December 16, 1959. The wind wave spectrum during that period of time did not change significantly. From 18h of December 16th to 03h of December 17th the wind veered and strengthened up to 62 knots. The wave spectrum was growing quickly and reached its peak by 18h of December 17. Then it weakened a little following corresponding decrease in the wind speed and again strengthened reaching the maximum at 0h of December 18th. Subsequent variations of the spectrum correspond to the storm wave decay.

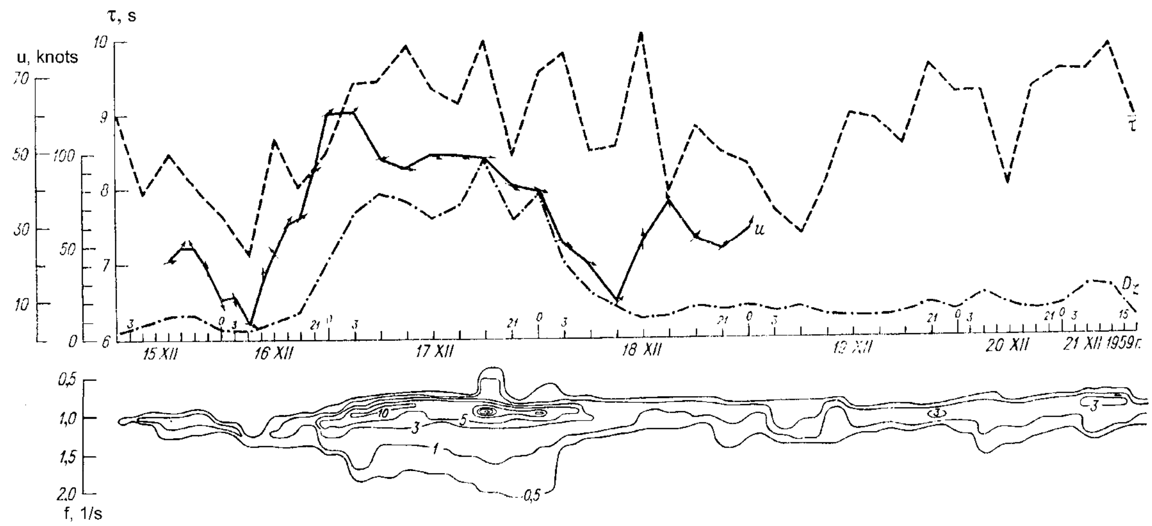


Fig. 1 An example of variations of frequency spectrum $S_\zeta(\omega,t)$ (m^2s). The upper panel: variations of total variance $D_\zeta(t)$ (m^2), mean wave period τ (s), and wind speed u (knots).

This example shows very good, that spectral density character even at wind and waves of equal intensity depends on waveformation prehistory. It does not take right to group wave weather states using trivial principle for unification (e.g. significant wave height) in determination of average for some class of spectra. Similar examples are included in chapter 11 of [8].

In any case linear wind waves, as a stochastic hydrodynamic process, are characterized by a directional spectrum $S_\zeta(\omega, \theta, \mathbf{r}, t)$, depending on the frequency ω, the wave direction θ, the spatial location **r**, and the time *t*. So for detailed description of any wind wave process including climatic wave states it is reasonable to apply this term, and Buckly's idea about climatic wave spectrum is good. Synoptic, annual and year-to-year variability produce, in turn, polymodulation of the associated wave field $\zeta(\mathbf{r}, t)$. By an *ensemble* of climatic wave spectra we mean a collection $\{S_\zeta(\omega, \theta, \mathbf{r}, t)\}$ for $\mathbf{r} \in R$, $t \in T$, where *R* is a spatial region, and *T* a time span of the order of decades.

The main objectives of spectral wave climate investigations are in broad terms

- to select classes of wave spectra and estimate their probability;
- to propose a parameterisation which allows one to justify a choice of difference between the various classes (i.e., the selection of discriminant variables);
- to approximate the ensemble $\{S(\omega,\theta)\}$ in terms of its probabilistic characteristics;
- to elaborate a stochastic model of the spectral wave climate;
- to estimate climatic wave spectra for extreme waves (design waves).

3. Parameterisation of climatic directional wave spectra

The main approach to presentation and calculation of climatic wave spectra is posed in papers [7-11]. It consists of wave spectra typification in frequency range in accordance with genetic set of patterns so as spectra in each class are geometrically similar each other and differ only in parameters correspondent to different waveformation. Such parameterisation of considered random functions (spectral density) is caused by wishes to simplify simulation of considered process. Standard approach to such simplification is presentation of random function with the help of deterministic function with a set of random parameters Ξ. The parameterisation allowed one to write wind wave spectra, $S_{ww,}$ and swell spectra, S_{sw} , as non-random functions

$$S = S(\omega,\theta,\Xi) \tag{1}$$

dependent on a set of random arguments, Ξ. The feasibility of an approach like (1) obviously depends on to which accuracy the spectrum $S_p(\omega,\theta)$ may be specified by the parameters Ξ_p taken from their multidimensional distribution $F_\Xi(\xi)$.

In the present study, parameters of the spectrum related to wave height, spectral shape, the frequency of the spectral peak, ω_{max}, and the main wave direction, θ_{max}, are selected as parameters in Ξ. The single field model spectrum may be written $S_p\left(\omega/\omega_{\max}, \theta-\theta_{\max}, \Xi_r\right)$, where Ξ_r signifies the rest of the parameters. More general spectra $S(\omega,\theta)$ are obtained as

$$S(\omega,\theta) = m_{00}\sum_{p=1}^{N}\gamma_p S_p\left(\frac{\omega}{\omega_p}, \theta-\theta_{\max}, \Xi_{r_p}\right) \tag{2}$$

where m_{00}, the 0[th] moment of the spectrum, is equal to the total variance of wave field, *N* is the number of wave fields (peaks in the spectrum), and γ_p are weight factors for each system so that, $\sum_{p=1}^{N}\gamma_p = 1$.

The following presentation is rather good for wind waves and swell:

$$S(\omega,\omega_{\max},n)=\frac{n}{\omega_{\max}}\left(\frac{\omega}{\omega_{\max}}\right)^{-n}\exp\left(-\left(\frac{n}{n-1}\right)\left(\frac{\omega}{\omega_{\max}}\right)^{1-n}\right), \tag{3}$$

Similarly, a well known directional distribution is

$$Q_0(\theta,\theta_{\max},m)=C_m\cos^m(\theta-\theta_{\max}),\quad |\theta-\theta_{\max}|<\frac{\pi}{2}, \tag{4}$$

where C_m is a normalizing parameter such that integral of function Q_0 from 0 to 2π is equal one, and the m parameter determines the width of the angular distribution.

Thus application of formulas (2)-(3) allows to describe each of N wave systems in wave spectrum (1) by the set of five parameters $\{\gamma_p, \omega_{\max\ p}, \theta_{\max\ p}, n, m\}$ that determine its shape and location. At that m_{00}, $\omega_{\max\ p}$, $\theta_{\max\ p}$ could be found directly from the spectra and we can apply Monte-Carlo method for n, m, γ_p estimation (see [9]).

The results of general procedure of spectra classification for Barents Sea carried are shown below. For calculations measurement data and data of hydrodynamic modeling were used. The following classes were select:

One-peaked spectra (I). One wave system prevails – either wind waves (I-1) or swell (I-2). In relation (2), N=1, γ_1=1, and only one extreme ($\omega_{\max}$, $\theta_{\max}$) occurs in the marginal $S(\omega)$ and $Q(\theta)$. The separation between wind waves and swell is based on *non-dimensional steepness* defined as

$$\delta=\frac{g\tau_{\max}^2}{h_s}=\frac{\pi^2 g}{\sqrt{m_{00}}\,\omega_{\max}^2}$$

If $\delta>300$, then spectrum belongs to a swell, otherwise to wind waves.

Two-peaked spectra (II). Two wave systems exist simultaneously. In relation (2) N = 2, $\gamma_1=\gamma$, $\gamma_2=1-\gamma$. We can recognize three subclasses (depending on the number of maxima in the marginal spectra):

II-1. <u>Mixed spectra with separation both in frequency and direction.</u> In this case, there are two pronounced maxima ($\omega_{max1},\theta_{max1}$), and ($\omega_{max2},\theta_{max2}$), both in the frequency spectrum and marginal angular distribution.

II-2. <u>Mixed spectra with separation only by direction.</u> In this case, there is one peak in the frequency spectrum and two peaks in the angular distribution. As a result in the two-dimensional spectra, there will be peaks at the same frequency ($\omega_{max1},\theta_{max1}$) and ($\omega_{max1},\theta_{max2}$).

II-3. <u>Mixed waves with separation only by frequency</u>. The angular distribution has only one peak and the frequency spectrum is broad with a not so pronounced second peak.

Multipeaked spectra (III). Complicated wave fields with two or more swell fields. In this case, the angular distribution has more than two pronounced peaks.

The estimated probability for belonging to each class of spectra in different months and during the year is presented in Table 1.

Table 1

The probability of classes of climatic wave spectra in the western part of the Barents Sea.

Classes	Subclass	Probability, %				
		January	**April**	**July**	**October**	**Annual**
I	**I–1**	45	42	32	48	42
	I–2	17	18	24	20	20
II	**II–1**	10	6	3	3	6
	II–2	22	25	30	25	26
	II–3	1	3	3	2	2
III	**III–1**	5	6	8	2	4

Examples of input one, two and multi-peaked spectra and their approximation by the model spectra are shown in the Fig.2.

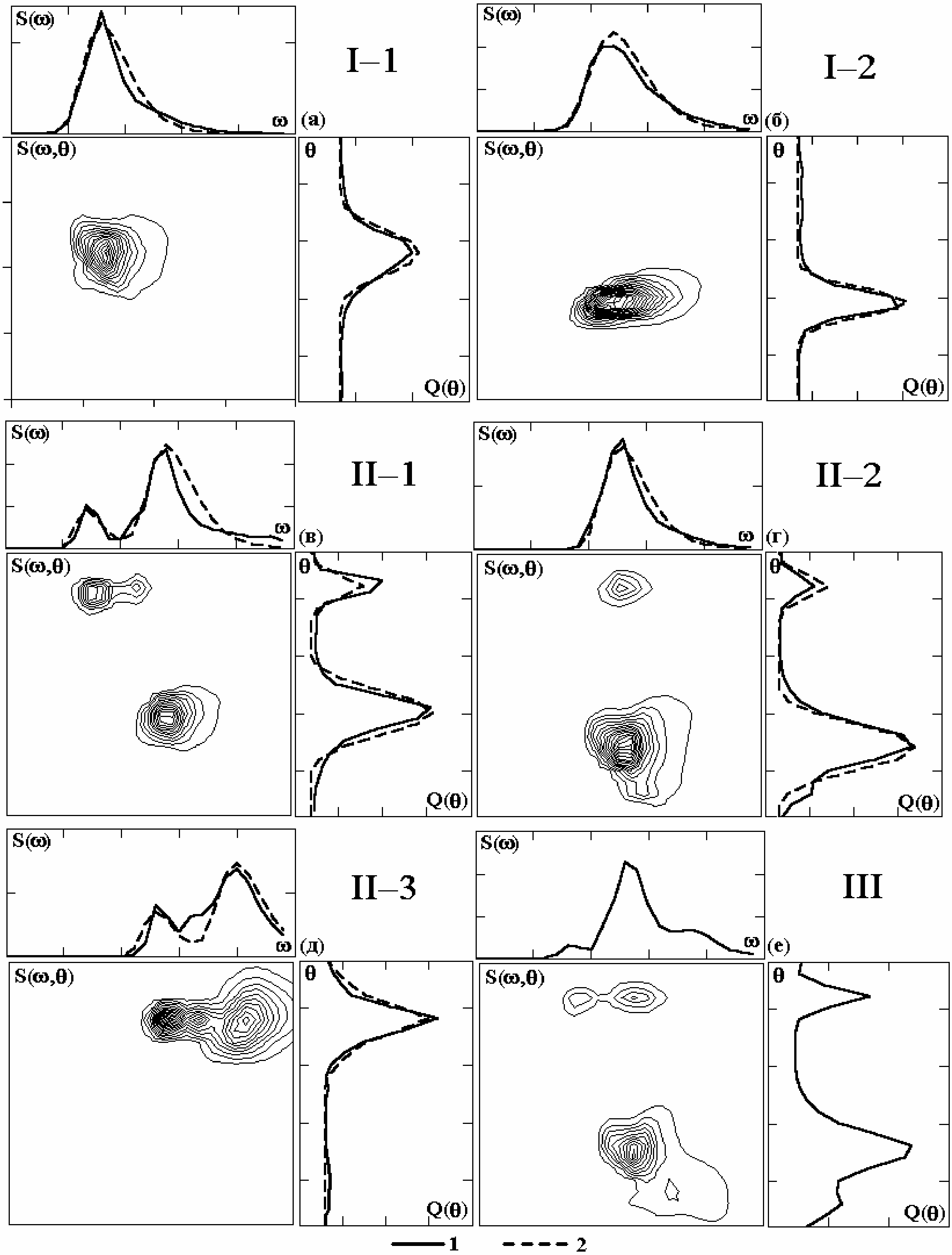


Fig. 2. Classes of climatic wave spectra. 1 – Hindcasting, 2 - Approximation

In fig. 3 the example of calculation of an average spectrum $S(\omega,\theta,\overline{\Xi})$ of complex waves (Northeast part of the Black Sea), and also correspondent probabilistic intervals is shown.

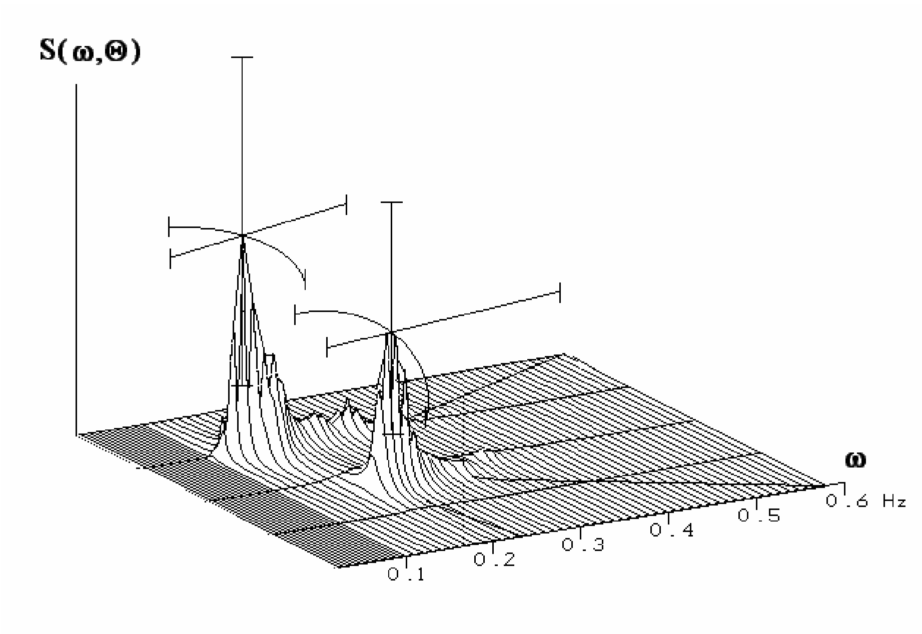


Fig.3. Frequency-directed climatic spectrum of complex sea. North-Eastern part of the Black Sea

4.Parametrisation of storms and good weather

Time series of wind wave heights in mid-latitudes and subtropical areas of the World Oceans make alternating sequences of storms and weather windows. We define a storm of duration $\Im$ and intensity h^+ as a situation when random function h(t) exceeds a predefined value Z. The period Θ during which the wave height is less than this threshold will be called a weather window of intensity h^- . The parameter δ shows the asymmetry of the storm: $\delta=(t_p-t_b)/\ \Im$, t_b, t_p , t_e are times of storm start, maximum development and end, respectively. Fig. 4 clarifies these definitions.

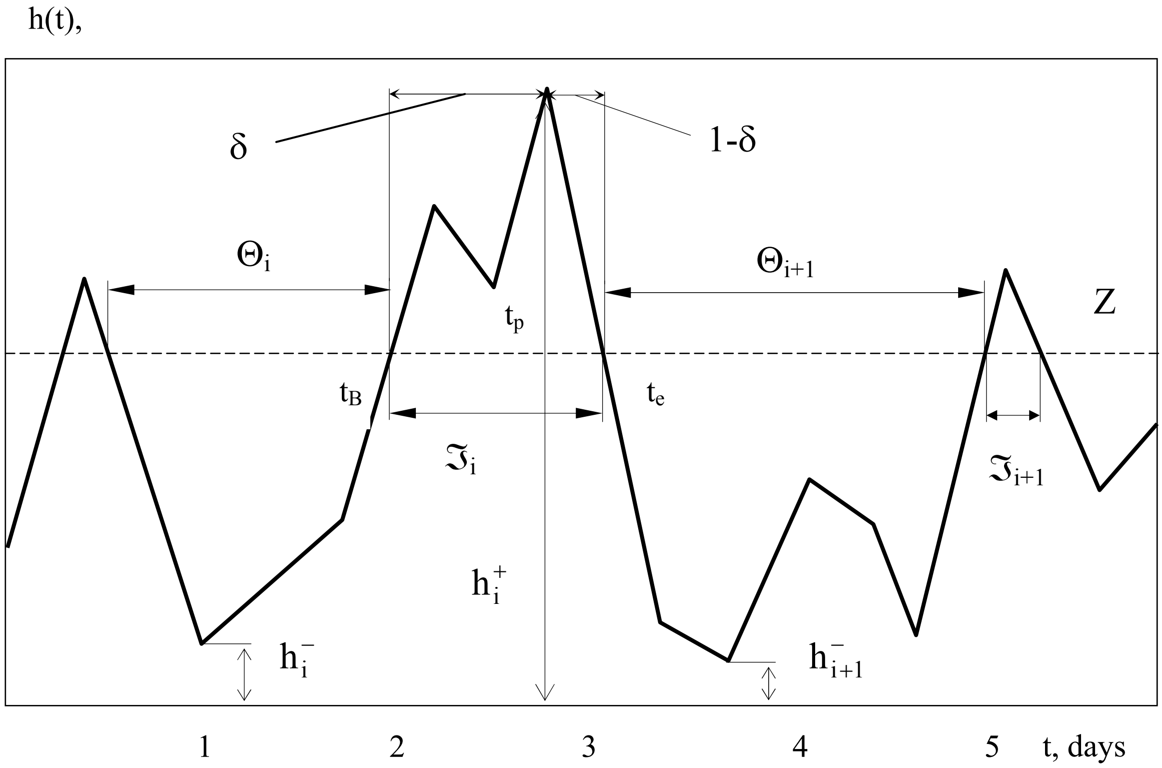


Fig. 4. Parameters describing storms and weather windows

Random functions $\Im$ and Θ represent duration of over-shots and under-shots. Therefore their distributions should asymptotically tend to the exponential law [19]:

$$F(x) = 1 - \exp\left(-\frac{x}{\bar{x}}\right) \tag{5}$$

Figs. 5 and 6 depict quantiles of distributions $F^*(\Im)$ and $F^*(\Theta)$ as the q-q bi-plots. It is seen that the hypothesis that $F^*(x)$ belongs to a class of exponential distributions can be confirmed. Hence m and σ should be nearly equal.

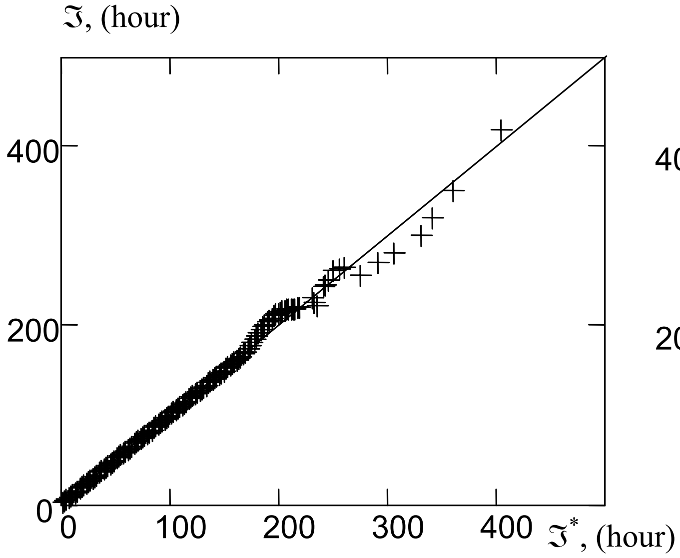


Fig. 5. Empirical distribution of storm duration $F(\Im)$ /quantile bi-plot of exponential distribution (5)/. The Baltic Sea.

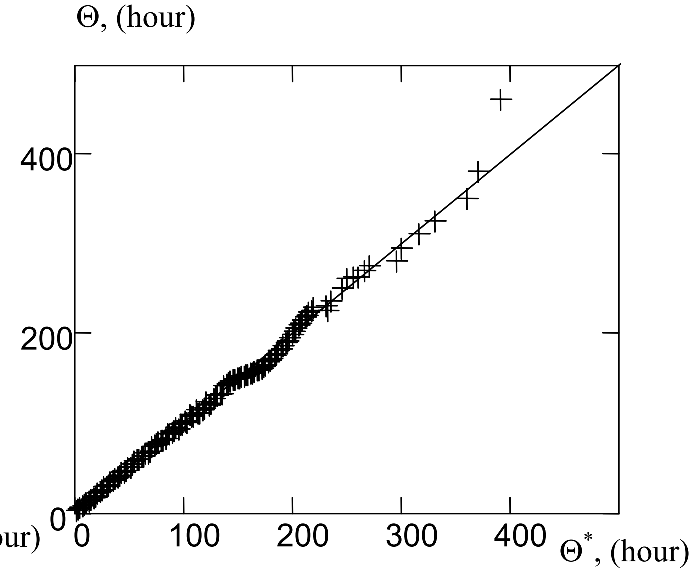


Fig. 6. Empirical distribution of weather window duration $F(\Theta)$ /quantile bi-plot of exponential distribution (5)/. The Baltic Sea.

Table. 2 gives correlation coefficients between different random functions in system $\{h^+, h^-, \Im, \Theta\}$

Table 2. Correlation coefficients ρ between impulse parameters

Values	(h^+,h^-)	(h^+,Θ)	$(h^-,\Im)$	$(\Im,\Theta)$	$(h^+,\Im)$	(h^-,Θ)
ρ	-0.1÷0.15	-0.15÷0.05	-0.1÷0.1	-0.1÷0.1	0.5÷0.8	-0.55÷-0.7

Hence, as the first approximation it is possible to consider parameters (h^+, h^-), (h^+,Θ), $(h^-,\Im)$, $(\Im,\Theta)$ independent while parameters (h^-, Θ), $(h^+,\Im)$ are dependent because their correlation coefficient is in range of 0.5−0.8. Hence, the four-dimensional distribution $F(h^+, h^-, \Im, \Theta)$ can be expressed as a product of two two-dimensional distributions $F(h^+, \Im)$ and $F(h^-,\Theta)$, each of them being equal to

$$F(x,y)=F(x)\,F(y|x) \tag{6}$$

i.e. to multiplication of marginal distribution F(x) and conditional distribution F(y|x) where $x = \{\Im,\Theta\}$ and $y = \{h^+, h^-\}$. Different approximations for distribution F are given in report [8].

Examples of storms classification are given by author and other scientists in many papers [7, 8, 20, etc.]. One of them (five storm classes specified for Black Sea [8]) is shown in table 3.

A matrix of probabilities that a certain storm category in 3 (for h=Z) will transform into another category is shown in Table 4. It follows from the table that there is some weak correlation between categories of consecutive storms.

Table 3. A classification of storm shapes

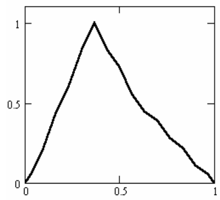
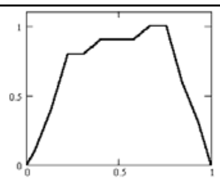
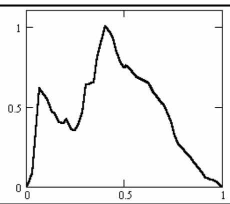
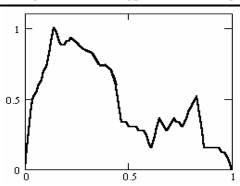
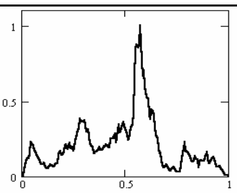
Category	Non-dimensional shape abscise is $(t-t_b)/\Im$ ordinate is h/h^+	Threshold Z=1.0 $\overline{\overline{h}}(t)$, $\overline{\overline{h}}(t)$ being mean seasonal wave height				Threshold Z=2.0 $\overline{\overline{h}}(t)$, $\overline{\overline{h}}(t)$ being mean seasonal wave height			
		P, %	N	Wave height h (cm)	Duration S (hour)	P, %	N	Wave height h (cm)	Duration S (hour)
I		**50%**	**110**	$h_{95\%}$=207 m_h=61 σ_h=57 $h_{5\%}$=21	$S_{95\%}$=45.5 m_S=11.0 σ_S=14.2 $S_{5\%}$=1.0	**49%**	**78**	$h_{95\%}$=241 m_h=105 σ_h=59 $h_{5\%}$=44	$S_{95\%}$=25.8 m_S=6.9 σ_S=8.0 $S_{5\%}$=0.7
II		**15%**	**33**	$h_{95\%}$=203 m_h=84 σ_h=54 $h_{5\%}$=22	$S_{95\%}$=71.7 m_S=28.7 σ_S=22.4 $S_{5\%}$=5.0	**24%**	**38**	$h_{95\%}$=267 m_h=121 σ_h=63 $h_{5\%}$=43	$S_{95\%}$=38.3 m_S=14.8 σ_S=10.3 $S_{5\%}$=1.8
III		**6%**	**13**	$h_{95\%}$=273 m_h=138 σ_h=75 $h_{5\%}$=33	$S_{95\%}$=95.5 m_S=44.9 σ_S=25.4 $S_{5\%}$=8.5	**13%**	**20**	$h_{95\%}$=207 m_h=137 σ_h=61 $h_{5\%}$=66	$S_{95\%}$=36.0 m_S=19.6 σ_S=11.0 $S_{5\%}$=5.0
IV		**19%**	**41**	$h_{95\%}$=273 m_h=108 σ_h=63 $h_{5\%}$=44	$S_{95\%}$=82.5 m_S=40.9 σ_S=23.3 $S_{5\%}$=12.2	**13%**	**20**	$h_{95\%}$=277 m_h=134 σ_h=60 $h_{5\%}$=42	$S_{95\%}$=110.5 m_S=34.0 σ_S=25.1 $S_{5\%}$=3.5
V		**10%**	**22**	$h_{95\%}$=197 m_h=104 σ_h=64 $h_{5\%}$=31	$S_{95\%}$=135.8 m_S=70.0 σ_S=41.5 $S_{5\%}$=9.5	**1%**	**2**	$h_{95\%}$=181 m_h=181 σ_h=1 $h_{5\%}$=180	$S_{95\%}$=184.5 m_S=118.8 σ_S=65.7 $S_{5\%}$=53.1

Table 4. Probability matrix of transformation of one storm category into another

Storm category	I	II	III	IV	V
I	0.5	0.1	0.1	0.2	0.1
II	0.3	0.1	0.2	0.2	0.2
III	0.6	0.2	0.1	0.1	---
IV	0.3	0.2	0.2	0.3	---
V	0.2	0.3	0.2	0.4	---

According to [21], it is possible to reconstruct conditions of a hypothetical (artificial) storm that would lead to the highest practically possible waves at a location of interest. The idea is to look at a situation that did not happen as yet but can, in principle, happen in future.

5. Probabilistic models for long-term spatio-temporal wave fields reproducing.

At the quasi-stationary and synoptic intervals of variability the wave process is best described by the stationary auto-regression model AR(p) of order p [11,22,23], namely

$$\xi_t = \sum_{k=1}^{p} \phi_k \xi_{t-k} + \varepsilon_t,, \qquad \zeta_t = f(\xi_t) \tag{7}$$

where ϕ_k are coefficients to be computed using correlation function $K_\xi(\tau)$, ε_t is white noise with a given distribution function, which has to be compatible with the nonlinear functional transformation $f(\bullet)$ of function ξ_t into, respectively, the Rayleigh or log-normal distribution of ζ_t.

In [8] it is shown that a stationary pulse-like random process is a good model for sequence of storms and fair weather intervals. A sample can be generated as follows:

$$\xi(t) = \sum_{k=1}^{n} w_k \left(Z, t - \sum_{j=1}^{k-1} \left(\Im_j + \Theta_j \right) \right) \tag{8}$$

where $\Im_j$ and Θ_j are, correspondingly, duration of storm and weather window (with threshold value Z),

$$w(Z,t) = \begin{cases} Z + \left(h^+ - Z\right)u(t/\Im)0 \le t \le \Im, \\ Z - \left(h^- - Z\right)u((t-\Im)/\Theta)\Im \le t \le \Im + \Theta \\ 0\;(t<0) \cup (t > \Im + \Theta) \end{cases}$$

h^+, h^- are the highest wave height in storm and the minimal wave height during the weather window. Function u(t) prescribes shape of the non-dimensional impulse. Triangular shape of this function looking as

$$u(t) = \begin{cases} t/\delta\; 0 \le t \le \delta, \\ 1/(1-\delta) - t/(1-\delta)\delta \le t \le 1 \\ 0(t<0) \cup (t>1) \end{cases}$$

serves as a good first approximation. Parameter δ, as seen from fig. 4, sets asymmetry of function u(t). If δ=0.5, the function is symmetric.

Actual generation of a series of random storms and weather windows is based on the Monte Carlo approach. It makes possible to reproduce the whole variety of values of $\{h^+, h^-, \Im, \Theta\}$:

$$\begin{aligned} \Im_k &= F_\Im^{-1}\left(\gamma_1^{(k)}\right), \Theta_k = F_\Theta^{-1}\left(\gamma_2^{(k)}\right) \\ h_k^+ &= F_{h^+|\Im}^{-1}\left(\gamma_3^{(k)} \mid \Im_k\right), h_k^- = F_{h^-|\Theta}^{-1}\left(\gamma_4^{(k)} \mid \Theta_k\right) \end{aligned} \tag{9}$$

Here $\left\{\gamma_i^{(k)}\right\}$ denotes a system of four pseudo random numbers.

Stochastic model for extra-annual rhythms could be written as follows:

$$\zeta(t) = m(t) + \sigma(t)\xi_t \tag{10}$$

Here m(t) and $\sigma(t)$ are periodic functions, and ξ_t is a non-stationary process AP(p) so that

$$\xi_t = \sum_{k=1}^{p} \phi_k(t) \xi_{t-k} + \varepsilon_t \tag{11}$$

Coefficients $\phi_k(t) = \phi_k(t+T)$ are periodic functions of time.

A model that is capable to describe year-to-year variability of monthly mean wave heights will therefore require twelve values of m(t) and 78 values of $K(t,\tau)$. It is possible to reduce the number of dimensions by considering the following representation of PCSP:

$$\zeta(t) = \sum_{k=-\infty}^{\infty} \eta_k(t) \exp\left(i\omega_k t\right) \tag{12}$$

Here $\eta_k(t)$ are stationary random processes (components) with mathematical expectation m_k and co-variation function $K_k(\tau)$ that can be obtained by expressing functions m(t) and $K(t,\tau)$ as the

Fourier expansion series. A simpler model for PCSP can be obtained by expanding function ξ(t) for *each* annual interval, as follows:

$$\zeta(t) = a_0 + \sum_{k=1}^{q} \left(a_k \cos \omega_k t + b_k \sin \omega_k t \right) \tag{13}$$

where a_k and b_k are random values, and q is the order of the model.

For a stationary process it is possible to suppose that values a_k and b_k are independent, while for a non-stationary process they will be dependent. Table 5 gives average values of means(m_{a_k}, m_{b_k}) , variances(D_{a_k}, D_{b_k}), co-variation $K_{a_k b_k}$, and correlation $\rho_{a_k,\, b_k}$ for coefficients of the model of annual rhythms. Hence, instead of model (10-11) with 90 parameters, a simpler model (13) with 20 parameters may be used. Monthly mean values of wave heights in the Black Sea were used for the computations. Corresponding values of m(t) and D(t) are shown in Fig. 7.

Table 5.

Statistical parameters of coefficients a_k, b_k of monthly means wave height rhythms model (13).

The Black Sea

Parameter	m,cm	D, cm^2	K_{a_k,b_k} (cm^2) and $\rho_{a_k,\, b_k}$				
			a_0	a_1	b_1	a_2	b_2
a_0	80	22	**1**	0.66	0.54	0.22	0.60
a_1	19	42	20	**1**	0.21	0.65	0.47
b_1	12	17	11	6	**1**	-0.26	0.52
a_2	2	39	6	26	-7	**1**	0.15
b_2	4	19	12	13	9	4	**1**

Note: co-variation K_{a_k,b_k} is given below diagonal and correlation coefficient $\rho_{a_k,\, b_k}$ is given above the diagonal.

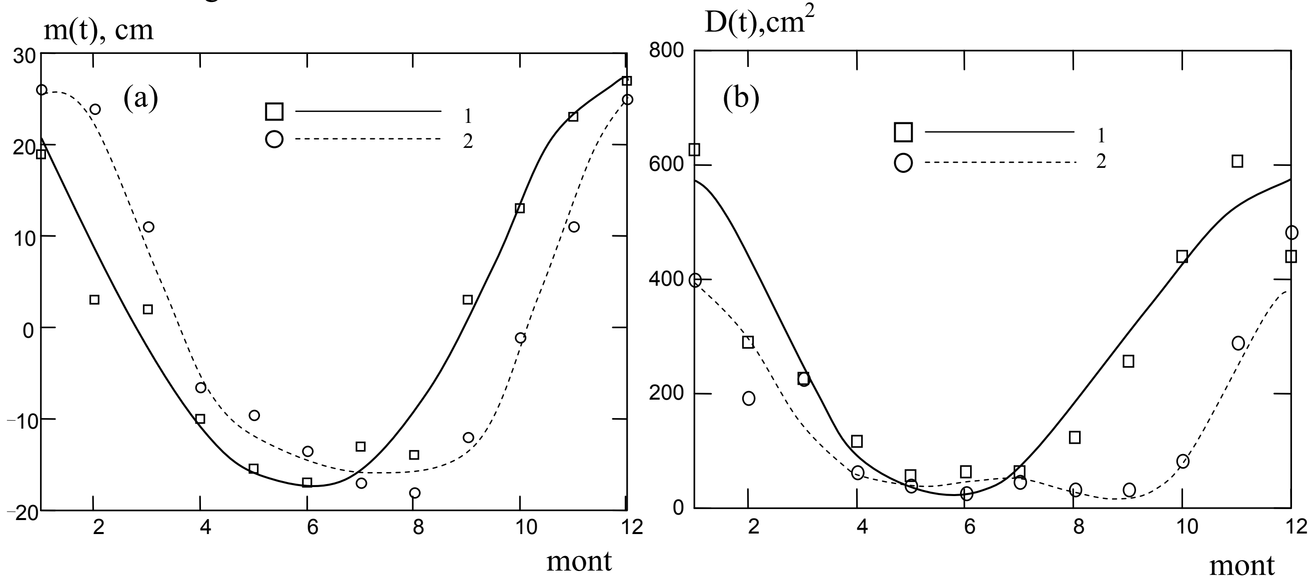


Fig.5.Mathematical mean (a) and variance (b) of monthly mean wave heights. All values are centered with respect of the mean annual wave height:(1)–The Baltic Sea, (2)–The Black Sea.

6. Scenarios of wave weather as initial data in seaworthiness problems.

Such approach to wave weather evolution presentation in considered water space permits to develop mathematical model of sea waves for long-term periods. The main characteristic of this model is multiscale, i.e. taking into account different time intervals: quasistationarity, synoptic variability, season and year-to-year variability. So it is possible to obtain ensemble of wind wave fields realizations of any time length.

Thus introduction of “climatic wave spectrum” and “wave climate” definitions result in expansion of design conditions base of external action for ship’s dynamic problems solution. Now instead of traditional poor set of some integral parameters (significant wave height, spectrum approximation, etc.) we can introduce new concept – ***wave weather scenario***. It can take into account subject to considered problem the following items:

- peculiarities of wave formation conditions – wind waves, swell, complex sea;
- geographical features of considered region;
- variability of hydrometeorological conditions – features and characteristics of storms evaluation and good weather permanence;
- scenarios of synoptic variability – alternation of storms and good weather states;
- characteristics of season variability – features of summer, winter time and off-season for considered navigation regions, special missions carried out by ship, etc.;
- long term presence of ship in given region or in known exploitation conditions comparable with life time of considered object.

In this case it is possible to propose for using in problems of research design, seaworthiness safety estimation, risk assessment for ships and offshore structures the following scenarios of wave weather:

- ***short-term scenario*** – modelling of spatio-temporal wave fields realizations taking into account all counted before peculiarities;
- ***scenario “storm”*** – wave actions modelling for typical storms in given region and season;
- ***scenario “mission”*** – variation of wind and wave conditions and external actions on ship during specific mission carrying out: voyage, rescue operation, ship raising, survey operations, combat mission, etc.;
- ***scenario “navigation”*** – consequence of ordinary scenarios “mission” covering long period including some seasons such as fishery, long navigation;
- ***scenario “life time”***- taking into account year-to-year and climatic variability of given region where ships and offshore structures operate; first of all it devotes to risk estimation in complicated expansive open-sea objects insurance.

7. Wave weather sceneries modelling.

Initial statistical information about wind and wave regime in given region is required for sceneries creation with the help of the methods described before. Obviously it is impossible to obtain such information by the way of measurement data only. The most fundamental starting point for derivation of equations governing the wave spectrum evolution is the equation for the conservation of the wave action density N (see, e.g., [24,25]):

$$\frac{\partial N}{\partial t}+\frac{\partial N}{\partial \varphi}\dot{\varphi}+\frac{\partial N}{\partial \theta}\dot{\theta}+\frac{\partial N}{\partial k}\dot{k}+\frac{\partial N}{\partial \beta}\dot{\beta}+\frac{\partial N}{\partial \omega}\dot{\omega}=G \tag{14}$$

The action N is a function of latitude φ, longitude θ, wavenumber k, angle β between the direction of wave propagation and the parallel, angular frequency ω, and time t. G is net source function. It is represented as the sum of the input G_{in} by the wind, the nonlinear transfer G_{nl} by resonant wave-wave interaction, and the dissipation G_{ds}. There are some other terms (interaction with slowly variable currents, etc.) which are normally small. They are not included in the propagation operator.

Equation (14) describes functional relation between fields of atmosphere pressure, wind and waves. There are many calculation models based on (14) devoted to obtaining time-spatial wave field. All they are differ from one another by sources function presentation and computational layout. Present spectral wind wave models based on equation (14) are rather well developed. They incorporate a representation of all significant mechanisms affecting the wave spectrum evolution and are quite sophisticated numerically. Being forced by wind data (or atmospheric pressure), and data on boundary layer stability, the models compute two dimensional (with respect of frequency and direction) spectrum $S(\omega,\beta)$ at nodes $\vec{r}_i$ of numerical grid at times t_j.

The first wave model which was realized as world famous software is WAM-model [26]. The theory and methods of numerical simulation are continuously improved. Now we have new results and models (WAVEWATCH [27], PHIDIAS [28], TOMAWAC [29], INTERPOL [25]) for deep and (SWAN [30]) for shallow water.

Specific character of computer presentation of hydrometeorological fields information is large volume of used data and long time for calculation. Hence, application of high performance computers is necessary.

Any hydrodynamic model devoted to wave fields calculation requires in initial wind data in meshes of net domain with assigned discretization in time domain. Available information till recently was heterogeneous, fragmentary and discrepant. A significant advance in numerical wave hindcasts resulted from the NCEP/NCAR meteorological reanalysis project [31], wiich produced global data series of great interest to wave modelling. The use of the reanalysis products to drive the wave model removed many of the inhomogeneities present in earlier data sets. For example results have shown in fig.2,3 were obtained with the help of simulation using a $0.5^0 \times 1.5^0$ grid, covering the North Atlantic, Greenland, and the Norwegian and Barents seas. The full directional spectrum $S(\omega,\theta)$ was calculated at each grid points with 24 values in direction θ and 25 values in frequency. The time step was 6 hours so that in any point $\mathbf{r}$, a collection of more than 21000 spectra with more than 13 millions numerical values had to be considered.

At the same time it is necessary to note that such technology is rather rough as long as reanalysis information is presented with rough space resolution. It takes possibility to obtain general representation about atmosphere processes evolution. With the object of improvement of atmosphere parameters it is possible to use special interpolation procedures [32] or to use regional models of atmosphere circulation. There are well-known such models as American model MM5 and European model HIRLAM. These models permit to calculate parameters of atmosphere boundary layer with high spatio-temporal resolution. These parameters include wind speed and direction, pressure, temperature, etc.

Codes of all mentioned model are open source. It is possible also to obtain detailed manuals of these software.

All these models permit to obtain initial information for statistical generalization, spectra parameterisation, storms classification and scenario wave calculations.

Then general algorithm for data preparation and realization of different scenarios looks like by the following:

1. Initial data of pressure fields preparation using reanalysis data for considered region or with the help of regional models of atmosphere circulation. Input of bathymetrical map, coastline and variation edge of the ice.
2. Verification of prepared data on the basis of comparison with natural observations. If occurrence of interpolation is bad than changing of model parameters for recalculation and go to i.1.
3. Wave fields calculation on the basis of model (14). Computational grid has to cover on the safe side considered region. It is necessary for taking into account influence of distant storms and incoming swell. Character of expansion of computational grid is defined by the expert evaluation taking into account geographical conditions of considered region. Time period of calculation depends on aims. 20-25 years are necessary for reliable statistical data. For purposes of extreme statistics this period has to be prolonged up to 30-40 years.

4. Verification of wave fields with the help of waves measurements in considered region (if we have long buoy records). Correction of model parameters and recalculation i.3 if big error of statistical characteristics exists (e.g. see [32]).
5. Assimilation of calculated data and measurements
6. Statistical treatment of obtained spatio-temporal wave fields and measurement data
    a. calculation of trivial statistics;
    b. determination of statistical parameters characterized storms and good weather periods (weather window);
    c. storms and weather windows classification;
    d. parameters of storms and weather windows interchange;
    e. climatic wave spectra classification;
    f. extreme statistics calculation;
    g. calculation parameters related with extreme waves.
7. Data assimilation for models of wave scenarios operation.
8. Using of year-to-year rhythmic model for climatic variation of wave weather reproduction in given region.
9. Superposition of climatic variations and results of probabilistic modelling of annual rhythmic.
10. Superposition of obtained results and results of stochastic modelling of storms and weather windows interchange.
11. Stochastic modelling of climatic spectra consecution corresponding to classes of storms and weather windows.
12. Time variation of frequency-directional spectra reproduction on the basis of obtained realization of average wave height and climatic spectra consecution.
13. Spatio-temporal wave fields generation for each wave spectrum.
14. Subject to solving problem and considered time scale reiteration of i.i.8-13 or collecting wave scenario ensembles.

8. Conclusion

Considered models are in framework of united probabilistic-hydrodynamic approach. Such full set of the models changes general approach to problem of external forces acting on ship. Introducing of “climatic spectrum” definition permits to create ensembles of wave weather scenarios and to use them for marine object behaviour simulation. Thus weather scenario is generalization and new level in assignment of external conditions in seaworthiness problems.

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