NUMERICAL EVALUATION OF WIND SEA–ROUGHNESS CHARACTERISTICS IN SIMULATION OF RADIATIVE CHARACTERISTICS FOR ATMOSPHERE–OCEAN SYSTEM

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Feasibility and outlook for using simplified method for computation of wind sea–roughness characteristics are discussed as well as the computation of sea–wave elements for different sea water areas of the Black Sea are analysed.

The wide use of results of remote sensing of ocean surface from space in a lot of scientific and applied problems requires much more accurate and reliable satellite information, whose quality is connected with a number of factors, among which are the capabilities of satellite instrumentation employed, choice of scheme for solving an inverse problem, optimal consideration of atmospheric and sea surface conditions, etc. The spaceborne remote sensing of the World Ocean and solution of electromagnetic radiative transfer equation for the ocean--atmosphere system are both impossible without regard for sea surface roughness parameters, mainly determined by the near-ground wind speed and influencing substantially the surface emission.

Sensed radiation from ocean surface $I_s(\lambda, \theta)$ (in accordance with Ref. 1) is in fact the sum of two contributions, I_o and I_r, its own and reflected by surface radiation, given by the expressions

$$I_o(\lambda, \theta) = I_s(\lambda, \theta)\, B_\lambda(T_s, \theta)\ ; \qquad (1)$$

$$I_r(\lambda, \theta) = r(\lambda, \theta)\, I_a^{\downarrow}(\lambda, \theta) = [1 - \varepsilon\,(\lambda, \theta)]\, I_a^{\downarrow}(\lambda, \theta)\ , \qquad (2)$$

where λ is the spectral range, θ is the zenith angle, B_λ is the Planck function dependent on temperature of emitting layer T_s, r is the reflection coefficient, and ε is the sea water emissivity.

For the rough ocean surface, the expression (2) is modified to

$$I_r(\lambda, \theta) = [1 - \varepsilon\,(\lambda, \theta)]\, I_a^{\downarrow}(\lambda, \theta^*)\ , \qquad (3)$$

where θ^* is the reflection angle (θ^* equals θ for perfectly smooth surfaces).

Note that the parameters $\varepsilon(\lambda, \theta)$ and θ^* depend on the degree of sea surface roughness (the level of sea waves).

Analysis of available literature (see, e.g., Ref. 2) shows that the sea surface emissivity ε is generally treated theoretically, mostly by means of some assumptions. In particular, changes in the sea surface emissivity due to wind sea–roughness are disregarded almost completely in calculations (due to the complexity involved), although this roughness is known to yield considerable variations in tilt angles and extents of local areas on water surface and, hence, in illumination and electromagnetic scattering conditions.

Recognizing all of the above mentioned, the present paper proposes one more method for calculating the wind sea surface roughness parameters, based on some empirical relations.

An extended body of experimental data about wind water roughness are available now (see, for example, Refs. 3 and 4). The empirical material concerning the statistic regularities of sinoptic, seasonal, and long–term distributions of wind and waves is considered in Refs. 5–11 in detail. However, this material is outdated due to the episodical character of wind water roughness observations, normally conducted in special sea expeditions. So, scientific and applied problems are solved in practice using a variety of calculation techniques. Modern methods of evaluation of sea waves from wind fields can be conventionally divided into three classes.[5]

1. Discrete spectral methods, which are based on the numerical solution of balance equation for wave intensity of the form

$$\frac{\partial E}{\partial t} + \frac{\partial}{\partial x}(E\ U) = E_\nu - E_\mu\ , \qquad (4)$$

where $E = gh^2/8$ is the wave intensity, $U = c/2$ is the wave group velocity (with the wave phase velocity c), E_v is the energy transferred to wave by wind, and E_μ is the energy loss due to dissipation.

The main weakness of the spectral methods is insufficient knowledge of the source function (responsible for formation of wind sea–roughness spectrum and including the mechanism of wave generation by wind, energy dissipation, and nonlinear energy redistribution over the wave spectrum), as well as high computation costs even with modern computers.

2. Parametrical spectral methods, which accomplish transition from energy balance equation, solved for every spectral component, to equation for spectrum parameters under the assumption of the universality of the latters. These models make use of the analytical approximation of wind sea–wave spectrum[5] and empirical relations between the spectral and wind parameters. However, the use of these methods is substantially reduced in practice, for the reasons of a number of assumptions adopted as well as due to many insufficiently grounded relations employed.

3. Empirical relations, which relate mean or relative values of wave elements to wind parameters. These are described best of all in Refs. 4, 9, and 12.

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We have used the third method for estimating the wind sea roughness elements (e.g., wave amplitude h, wave length λ, and wave period τ) because of its simplicity, sufficient reliability, and computation efficiency.

In the most general case, as it follows from Ref. 12, any wave element (or sea roughness parameter) is a function of three variables: the wind velocity v, the starting length x, and the wind duration t_v (e.g., $h = f(v, x, t_v)$). If the wind duration is long enough to develop maximum waves for a given starting length, then $h = f(v, x)$.

Under ordinary conditions of wave formation, i.e., for wind velocity constant in space and time, the numerical relations between wave elements, starting length, and wind velocity may be written as[12]:

$$g\bar{h}/v^2 = 0.0042\,(gx/v^2)^{1/3}\,; \tag{5}$$

$$g\bar{h}/v^2 = 0.0013\,(gt_v)^{5/12}\,, \tag{6}$$

where x and t_v are related as

$$gt_v/v = 17.3\,(gx/v^2)^{4/5}\,, \tag{7}$$

while the relation for the mean period $\bar{\tau}$ is of the form

$$g\bar{\tau}/v = 18.7\,(g\bar{h}/v)^{3/5}\,. \tag{8}$$

The relative mean wave length assumes the form

$$\bar{\lambda} = (g/\bar{\tau}^2)\,2\pi = 1.56\,\bar{\tau}^2\,. \tag{9}$$

In Eqs. (5)–(9), h, x, and λ are given in meters, τ and t_v – in seconds, v – in m/s, and $g = 9.81$ m/s is the acceleration due to gravity.

Quantities $g\bar{h}/v^2$, $g\bar{\tau}/v$, gx/v^2, and gt_v/v are, respectively, called as dimensionless mean amplitude, dimensionless mean period, dimensionless starting length, and dimensionless wind duration. These dependences are obtained assuming the wind velocity constant in starting length, while gx/v^2 ranges between 50 and 60 000, that is close to real values in ocean.

Also of utility in calculations of sea wave elements is the average wind velocity $\bar{v}$. Then they can be evaluated in the limits $x/v^2 \geq 6000$ and $t_v/v \geq 3.2$ as

$$\bar{h}/v^2 = 0.0016,\quad \bar{\lambda}/v^2 = 0.64,\quad \bar{\tau}/v = 0.64\,,\quad \bar{c}/v = 1\,, \tag{10}$$

that corresponds the extreme sea wave evolution.

Thus, having the coordinate of observation known, it is possible to consider the wave formation situation most typical for the open and deep ocean, i.e., the presence of wind, constant in starting length and time, with duration sufficient to yield steady sea waves.

Characteristics of sea wave regime (with a provision $F \cong 50\%$), represented by amplitude $\bar{h}$, period $\bar{\tau}$, and length $\bar{\lambda}$, are calculated now from empirical relations (10) as

$$\bar{h} = 0.16\,v^2\,,\qquad \bar{\lambda} = 0.64\,v^2\,,\qquad \bar{\tau} = 0.64\,v\,. \tag{11}$$

The transition to sea wave elements of any other provision can be made using transition coefficients (presented in Table I).

TABLE I.

F, %	0.1	1.0	5.0	10	20	30	50
$\kappa_{h/\bar{h}}$	3.20	2.52	1.91	1.69	1.39	1.21	0.93
$\kappa_{\tau/\bar{\tau}}$	1.78	1.65	1.47	1.37	1.23	1.15	1.00
$\kappa_{\lambda/\bar{\lambda}}$	–	2.52	1.94	1.71	1.44	1.26	0.93

Therefore, quantities h_f, λ_f, and τ_f for a given provision are readily found from their calculated mean values using relations

$$h_f = \kappa_h\,\bar{h}\,,\qquad \lambda_f = \kappa_\lambda\,\bar{\lambda}\,,\qquad \tau_f = \kappa_\tau\,\bar{t}\,. \tag{12}$$

The values so obtained are verified through the following limiting values: $h \leq \lambda/7$ and $c/v = \lambda/(\tau\,v) \leq 1$, where c is the phase velocity of evolving wave (up to the appearance of swell).

An example: let $\bar{h} = 2.5$ m, then Table I and formula (12) give us an amplitude of a wave with a provision of 5% $h_{5\%} = \bar{h}\cdot 1.91 = 4.77$ m.

In the present paper, the above method is used to calculate the mean values of wind sea wave elements for various areas of the Black Sea. This was done using oceanological database of Russian State Meteorological Institute. This last consists of the climatic data on monthly mean temperatures of ocean surface and near-surface wind characteristics calculated in nodes of 1° geographic grid.

As an example, Table II presents the calculations of wind sea wave elements for January and July, made using near-surface wind data for three squares corresponding to the West, Central, and East areas of the Black Sea.

Table II indicates that wind sea wave elements are highly variable both in space and time even within the Black Sea area. For example, in winter the waves in the Black Sea area range between 4.8 and 10.1 m in amplitude, 19.5 and 40.5 m in length, and 3.5 and 5 s in period. In summer, sea wave elements have much less variations, with values ranging between –2.3 and 3.9 m in wave amplitudes, –9.2 and 15.7 m in wavelength, and –2.4 and 3.1 s in period.

Table II shows the close similarity of calculated sea wave elements to those obtained using other, more complex techniques (see Refs. 4–6). Therefore, this method is appropriate advantageous to be used for solving a wide range of applied problems, including spaceborne sensing of sea surface.

TABLE II. Example of calculation of the amplitude (h, m), length (λ, m), and period (τ, s) of wind sea waves for typical squares of Black Sea.

Coordinates, deg		Waves elements					
N	E	h, m	λ, m	τ, s	h, m	λ, m	τ, s
		January			July		
42.5	29.5	8.1	32.4	4.5	2.3	9.2	2.4
42.5	30.5	7.9	31.2	4.5	2.7	11.0	2.6
43.5	29.5	9.3	37.2	4.8	3.0	12.2	2.8
43.5	30.5	10.1	40.5	5.0	3.9	15.7	3.1
42.5	32.5	6.4	25.8	4.0	2.7	11.0	2.6
42.5	33.5	7.2	28.9	4.3	2.7	10.8	2.6
43.5	32.5	8.8	35.5	4.7	3.3	13.2	2.0
43.5	33.5	6.9	27.8	4.2	2.4	9.8	2.5
42.5	37.5	5.1	20.7	3.6	2.5	10.1	2.5
42.5	38.5	4.8	19.5	3.5	2.4	9.9	2.5
43.5	37.5	8.5	34.4	4.6	3.8	15.2	3.1
43.5	38.5	6.5	26.2	4.1	2.7	10.9	2.6

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