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EFFECT OF FOAM ON THE OCEAN-ATMOSPHERE BRIGHTNESS FIELD

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An analytical expression is derived for calculating the brightness of upward radiation of the "ocean surface-atmosphere" system taking into account reflection from for different states of the atmosphere, the wind velocity, and geometry of illumination and observation. It is shown that changes brought about in the coverage of the ocean surface by foam and in the albedo of the foam by changes in the physical and chemical properties of the ocean water result in significant variations in the brightness of the upward-directed radiation at the top boundary of the atmosphere.

In order to expand the possibilities of remote determination of the concentration of impurities in ocean water (chlorophyll pigments, mineral suspension, etc.) the algorithms used for introducing atmosphere corrections must be improved.[1] One way to improve the reliability of these algorithms is to employ more accurate models describing the propagation of visible and near-IR radiation in the atmosphere above the sea surface.

The atmospheric-correction algorithms are based on the relation[2]

$$B_W(\lambda_i) = [B(\lambda_i) - B_{R+a}(\lambda_i)]/t(\lambda_i), \tag{1}$$

where $B_W(\lambda_1)$ is the spectral brightness of the radiation emanating from the ocean; $B(\lambda_1)$ is the brightness of the radiation recorded by the sensor at the top boundary of the atmosphere; $B_{R+a}(\lambda_1)$ is the brightness of the radiation scattered by the molecules of the atmospheric gases (Rayleigh or molecular scattering) and by aerosol particles in the atmosphere (aerosol scattering); $t(\lambda_1)$ is the diffuse transmittance of the atmosphere; and λ_1 is the central wavelength of the ith spectral range.

The component $B_{R+a}(\lambda_1)$ in Eq. (1) includes the radiation only scattered in the atmosphere as well as radiation reflected from the ocean surface:

$$B_{R+a}(\lambda_i) = B_H^{R+a}(\lambda_i) + B_{AOS}^{R+a}(\lambda_i) + B_{OSA}^{R+a}(\lambda_i) + B_{OS}^{R+a}(\lambda_i), \tag{2}$$

where $B_H(\lambda_1)$ is the brightness of radiation scattered in the atmosphere (brightness of atmospheric haze); $B_{\mathrm{AOS}}(\lambda_1)$ is the brightness of radiation scattered in the atmosphere and reflected from the ocean surface (AOS); $B_{\mathrm{OSA}}(\lambda_1)$ is the brightness of the direct solar radiation reflected from the surface of the ocean and then scattered in the atmosphere (OSA); and, $B_{\mathrm{OS}}(\lambda_1)$ is the brightness of the direct solar radiation reflected from the ocean surface without scattering in the atmosphere (OS).

When Eq. (2) is calculated in the atmospheric-correction algorithms the ocean surface is assumed to flat or the effect of wind-driven waves on only the reflection of the direct solar radiation is taken into account.[2] In Ref. 3 expressions were derived for the dependence of the components of radiation reflected from the ocean surface B_{OS}, B_{AOS}, $\mathrm{B}_{\mathrm{OSA}}$ on the optical state of the atmosphere, the observation geometry, and the velocity of the driving wind. In this paper we shall study the reflection from the ocean surface taking into account foam, formed when the wind velocity increases above some threshold.

In the presence of foam and neglecting the double interaction of radiation with the "ocean surface-atmosphere" system the brightness of the radiation reflected from the ocean surface (neglecting reflection at the surface) B_{sf} can be written in the form

$$B_{sf} = C_f B_f + (1 - C_f) B_s, \tag{3}$$

where C_f is the fraction of the surface covered by foam; $B_s = B_{\mathrm{OS}} + B_{\mathrm{OSA}}$ is the brightness of the radiation reflected from the agitated, foam-free mean surface; and, B_f is the brightness of the radiation reflected from sections of the surface covered with foam.

Assuming that the foam is a diffuse reflector[4] with albedo A_f and using the single-scattering approximation in the atmosphere, (we shall represent the brightness of the radiation $B_f(\tau, \Theta)$ in the form

$$B_f(\tau, \Theta) = \frac{1}{\pi} A_f E_\Sigma \left\{ e^{-\tau/\cos\Theta} + \frac{1}{\pi} \int\limits_0^{2\pi} \int\limits_0^{\pi/2} \sigma_1(\tau, \Theta, \varphi, \Theta', \varphi') \cos\Theta' \sin\Theta' \, d\Theta' d\varphi' \right\} \tag{4}$$

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where

$$E_\Sigma = \pi S \cos\Theta_0 \left[e^{-\tau/\cos\Theta_0} + \right.$$
$$\left. + \frac{1}{\pi} \int_0^{2\pi} \int_0^{\pi/2} \sigma_1(\tau_0, \Theta'', \varphi'', \Theta_0, \varphi_0) \cos\Theta'' \sin\Theta'' d\Theta'' d\varphi'' \right] \quad (5)$$

is the illumination of the ocean surface by the direct and scattered solar radiation (S is the solar constant)

$$\sigma_1(\tau, \Theta_1, \varphi_1, \Theta_2, \varphi_2) = \frac{x(\gamma)}{4} \frac{\exp(-\tau/\cos\Theta_1) - \exp(-\tau/\cos\Theta_2)}{(\cos\Theta_1 - \cos\Theta_2)} \quad (6)$$

is the transmittance of a layer of the atmosphere with optical thickness τ in the single-scattering approximation;[5] $x(\gamma)$ is the scattering phase function of the atmosphere; γ is the scattering angle

$$\cos\gamma = \cos\Theta_1 \cos\Theta_2 + \sin\Theta_1 \sin\Theta_2 \cos(\varphi_2 - \varphi_1); \quad (7)$$

τ_0 is the optical thickness of the entire atmosphere; Θ and φ_0 are the zenith angle and azimuth of the sun.

With the help of Eqs. (5)–(7) and using the notation

$$t_{tr}(\tau_i, \Theta_i) = e^{-\tau/\cos\Theta_i} \quad (8)$$

$$t_{dif}(\tau_i, \Theta_i) = \frac{1}{\pi} \times$$
$$\times \iint \frac{x(\gamma)}{4} \frac{e^{-\tau_i/\cos\Theta'} - e^{-\tau_i/\cos\Theta_i}}{\cos\Theta' - \cos\Theta_i} \cos\Theta' \sin\Theta' \, d\Theta' d\varphi' \quad (9)$$

we write Eq. (4) in the form

$$B_f = A_f \, S \cos\Theta_0 \left[t_{tr}(\tau_0, \Theta_0) + t_{dif}(\tau_0, \Theta_0) \right] \times$$
$$\times \left[t_{tr}(\tau, \Theta) + t_{dif}(\tau, \Theta) \right]. \quad (10)$$

To calculate the integral in Eq. (9) we shall represent the scattering phase function $x(\gamma)$ as the first two terms in the expansion in Legendre polynomials

$$x(\gamma) \approx 1 + x_1 \cos\gamma,$$

where

$$x_1 = \frac{3}{2} \int_0^\pi x(\gamma) \cos\gamma \sin\gamma \, d\gamma$$

is the first expansion coefficient.

After a series of transformations we obtain

$$t_{dif}(\tau_1, \Theta_1) = 0.5(1 + x_1 \cos^2\Theta_1) \Big\{ e^{-\tau_1/\cos\Theta_1} \times$$
$$\times \Big[\cos\Theta_1 \Big[Ei(-\tau_1(1 - \sec\Theta_1)) - \ln|1 - \sec\Theta_1| \Big] - 1 \Big] +$$
$$+ e^{-\tau_1} + (\tau_1 - \cos\Theta_1) \, Ei(-\tau_1) \Big\} + \frac{x_1 \cos\Theta_1}{4} \times$$
$$\times \Big[e^{-\tau_1}(1 - \tau_1) - e^{-\tau_1/\cos\Theta_1} - \tau_1^2 \, Ei(-\tau_1) \Big], \quad (11)$$

where Ei(·) is the exponential integral function.

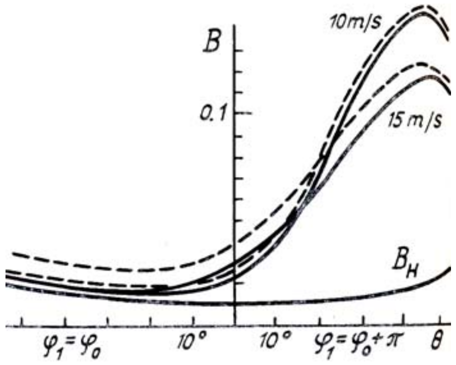

FIG. 1. The brightness of upward radiation of the "ocean surface-atmosphere" system. λ = 440 nm.

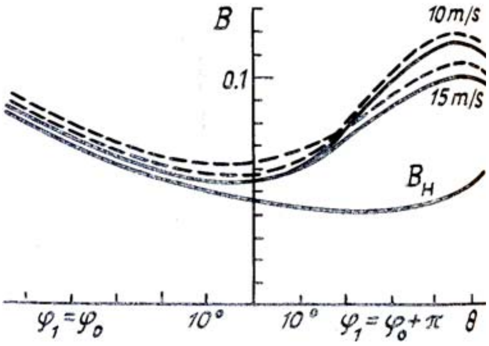

FIG. 2. The brightness of upward radiation of the "ocean surface-atmosphere" system. λ = 700 nm.

The expression (11) describes the transmittance of the atmosphere t_{dif} (9) with an insignificant error, which (for chosen conditions of observation and type of scattering phase function — Rayleigh, Henney-Greenstein, or model; for a marine aerosol[2] and $\tau < 0{,}9$) does not exceed 15%.

Thus the brightness of the radiation reflected from a foam-covered ocean surface is described by the expressions (3) and (10), and the values of $t_{tr}(\tau, \Theta)$ and $t_{dif}(\tau, \Theta)$ are calculated from the formulas (8) and (11), respectively.

Figures 1 and 2 show plots of the brightness of the upward radiation of the "ocean surface-atmosphere" system at the top boundary of the atmosphere in the spectral ranges $\lambda = 440$ and $\lambda = 700$ mm for different wind velocities. The calculations were performed under the following conditions

$$S = 1; \quad \Theta_0 = 40^\circ; \quad A_f = 0.5; \quad \tau_a(440) = 0.24;$$

$$\tau_a(700) = 0.2; \quad \tau_R(440) = 0.25; \quad \tau_R(700) = 0.037;$$

$$\tau_0(\lambda_i) = \tau_a(\lambda_i) + \tau_R(\lambda_i);$$

$$x_{\lambda i}(\gamma) = (\tau_a(\lambda_i)x_a(\gamma) + \tau_R(\lambda_i)x_R(\gamma))/\tau_0(\lambda_i).$$

Here the index "a" corresponds to the optical characteristics of an aerosol atmosphere and the index "R" corresponds to a Rayleigh atmosphere. The dependence of the degree of coverage with foam on the wind velocity was calculated using the empirical formula given in Ref. 6.

In Figs. 1 and 2 the solid lines show the brightness of the radiation reflected from the ocean surface neglecting foam and the brightness of atmospheric haze B_H while the dashed lines show the brightness of the reflected radiation taking into account the presence of foam. One can see from the figures that for wind velocity exceeding 10 m/sec the presence of foam significantly increases the brightness of the upward radiation, especially in the regions of the spectrum where the relative predominance of the aerosol increases the elongation of the scattering phase function of the atmosphere.

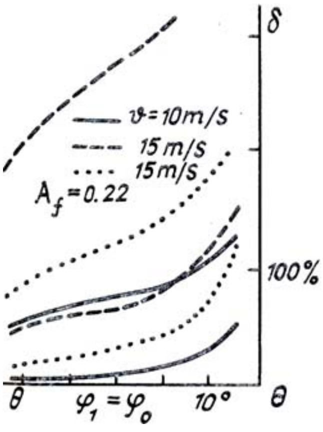

FIG. 3. The effect of the uncertainly in the choice of the model of foam formation on the brightness of the upward radiation.

In the calculation of the brightness of the radiation reflected from the foam-covered ocean surface the accuracy of the description of the dependence of the degree of coverage with foam C_f on the wind velocity and the choice of the value for the albedo of the foam A_f are very important.

Figure 3 shows the results of the calculation of the brightness of the upward radiation for wind velocities of 10 and 15 m/sec for different models describing the dependence of the degree of coverage of the ocean surface with foam on the wind velocity for ocean water with different physical and chemical properties.[6–7] The brightness of the radiation was calculated for the state of the atmosphere corresponding to a wavelength of $\lambda = 700$ nm (see the description in Fig. 2). The results are presented in the form of the relative correction to the brightness of atmospheric haze. One can see from the plots that the uncertainty in the calculation of the brightness of the radiation, caused by the uncertainty in the choice of the foam-formation model, is comparable the brightness of the radiation scattered in the atmosphere.

Another factor that makes it difficult to describe the radiation reflected from a foam-covered ocean surface is the uncertainly in the value of the foam albedo A_f. The albedo of a section of the foam-covered surface depends on the lifetime of a specific foam formation and decreases as the foam structure decay.[5] Thus the average albedo of all foam formations depends on both the intensity of foam formation and the lifetime of foam structures, determined by the physical and chemical properties of the ocean water. Figure 3 shows plots of the calculations of the relative correction caused by the presence of the foam with an average value of the albedo $A_f = 0.22$ (Ref. 4) for two extreme values of the degree of coverage with foam C_f with a wind velocity of 15 m/sec.

It should be noted that albedo $A_f = 0.22$ is much lower than the values used previously, since other authors employed values of the albedo that were measured under laboratory conditions for dense and fresh foam structures.

Thus in this work we have constructed a parametric model that describes the brightness of the upward radiation of the system "ocean surface-atmosphere" taking into account foam formations. The results of the calculations performed with the help of the parametric model show the following:

– the foam significantly increases the brightness of the upward radiation of the "ocean-atmosphere" system for wind velocities greater than 5–7 m/sec;

– for a wind velocity greater than 10 m/sec the uncertainty in the value of the foam albedo A_f and the dependence of the degree of coverage with foam C_s under different conditions result in a spread in the values of the brightness that is comparable to the brightness of the "ocean surface-atmosphere" system; and,

– in order for remote sounding above the ocean surface to be successful with wind velocities exceeding 7 m/sec the degree of coverage of the ocean surface with foam and the albedo of the form must be measured at the same time that the remote sounding is conducted.

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